Orbit and gradient error correction for eRHIC NS-FFAG design

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OUTLINE

PREVIOUS EXPERIENCE at RHIC

ORBITS WITH MISALIGNMENT and GRADIENT ERRORS

CORRECTIONS

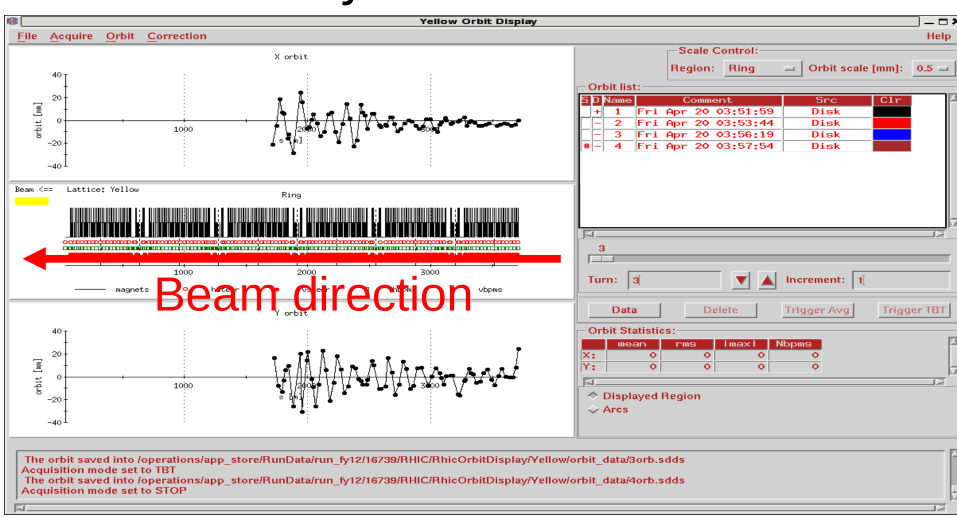
OVERALL PLAN

Previous experience at RHIC

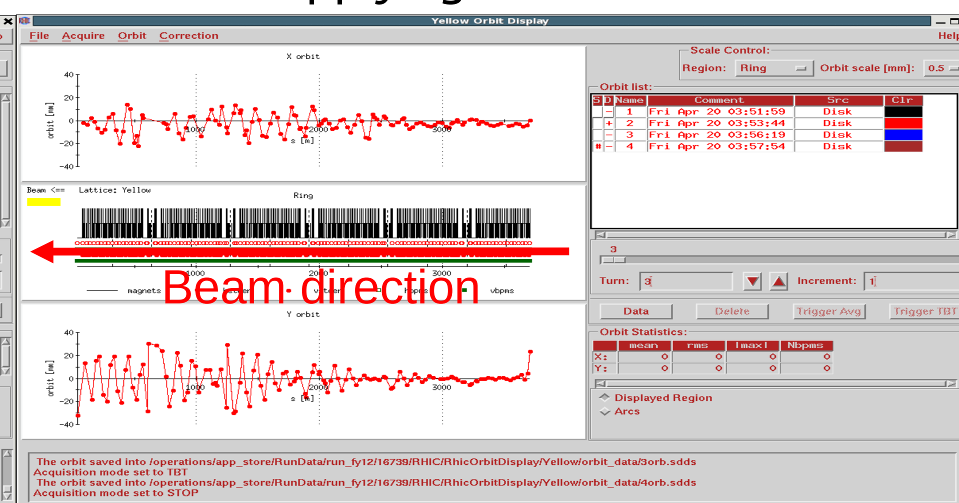
Orbit correction in RHIC

- Nine algorithms available for orbit correction
- Automated correction for injection steering
- Orbit feedback is applied for routine operation
- Orbit rms is ~20 um with orbit feedback

Orbit at first injection:

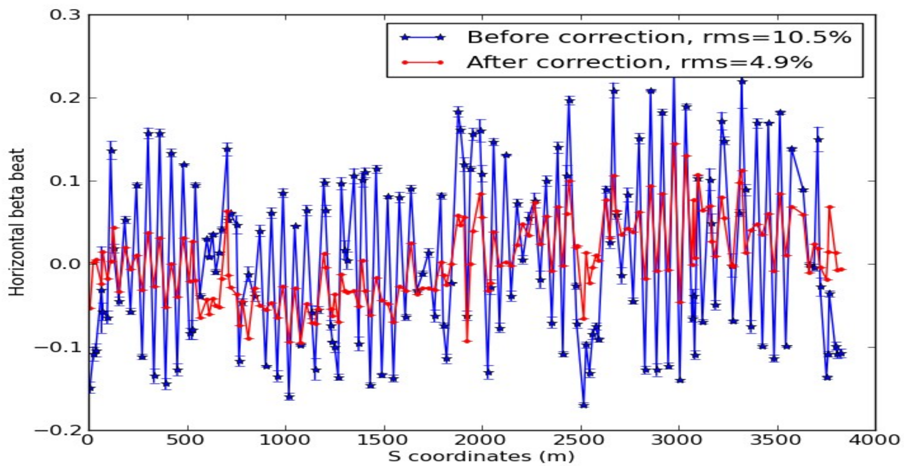


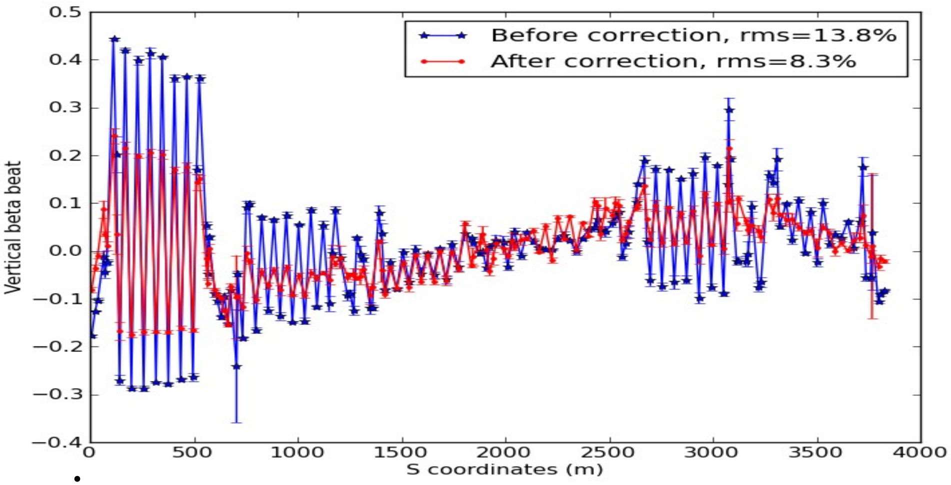
Orbit after applying First turn SVD:



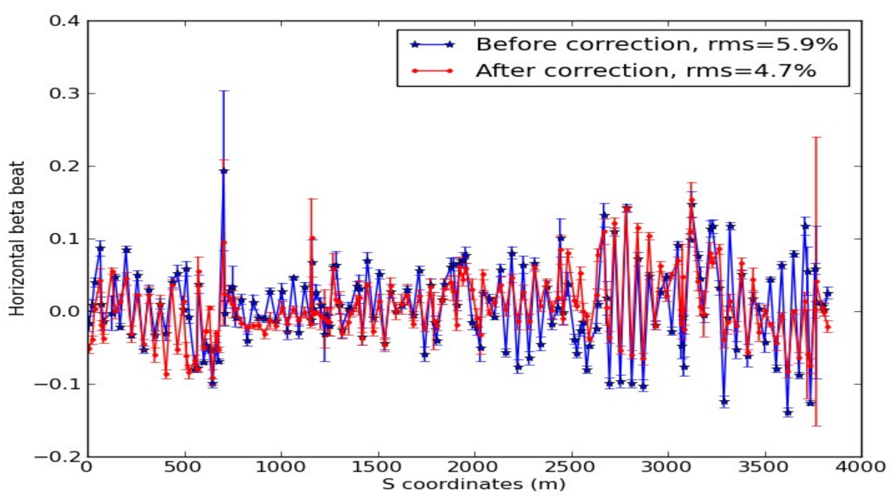
Optics correction in RHIC

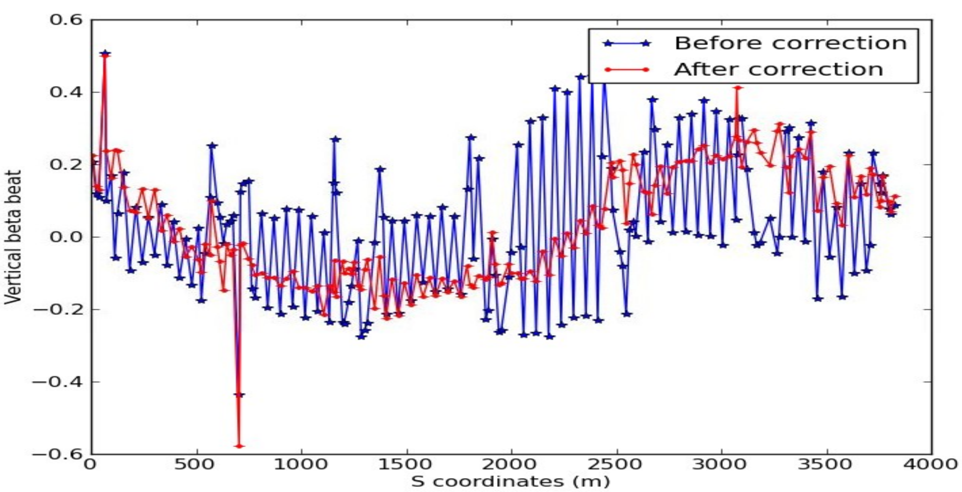
Blue ring





Yellow ring



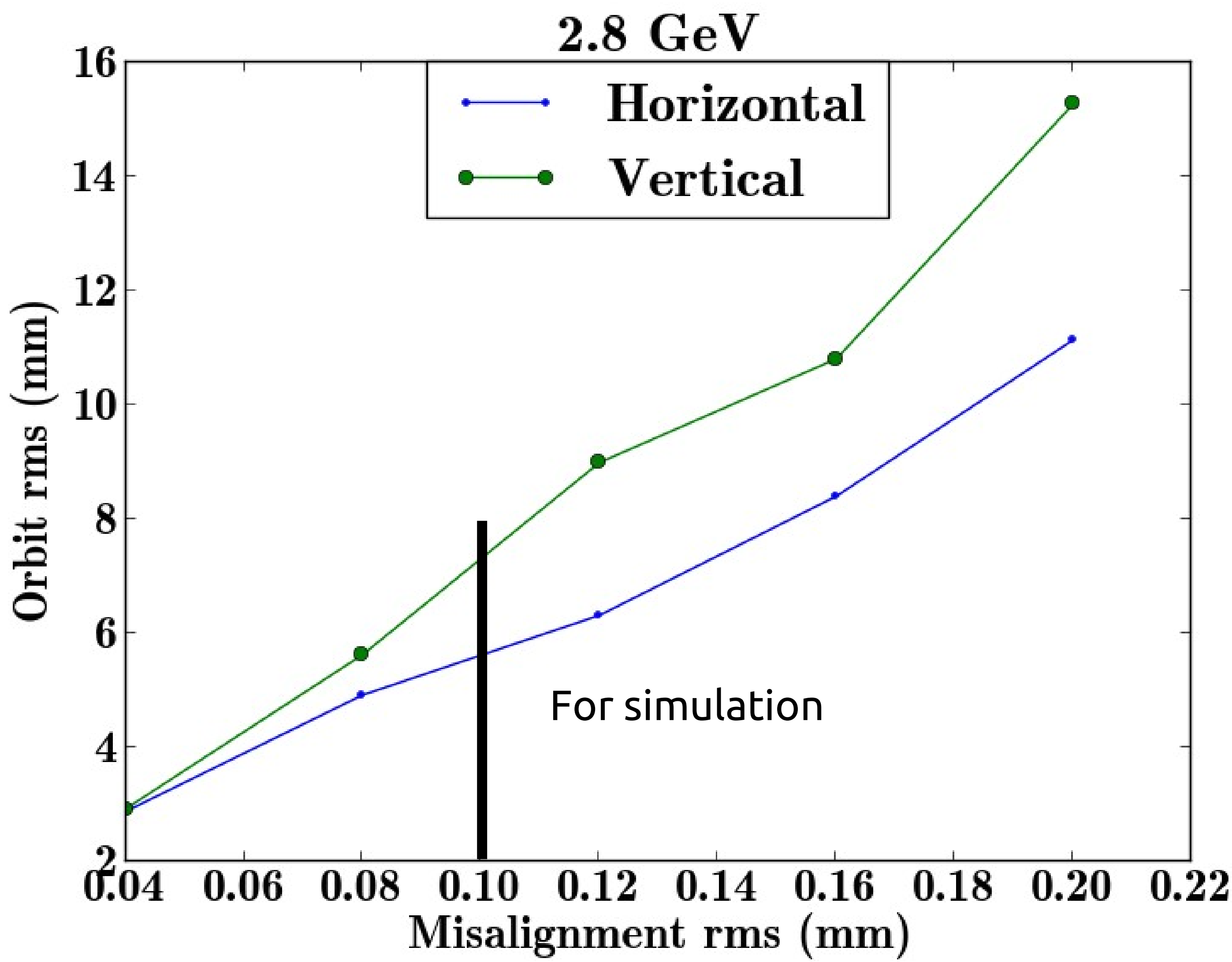


Status of optics correction

- Three types TBT data (Artus data, AC dipole, injection oscillation), three analysis techniques (fitting, Interpolated FFT and ICA) in function
- Breakthrough of global optics corrections based on both Artus and AC dipole data
- Ramp optics measurement with Artus in operation
- Rotator ramp optics correction operational since May 2013
- Energy ramp optics correction in progress

Orbits with misalignment and gradient errors

Orbit distortion due to misalignment



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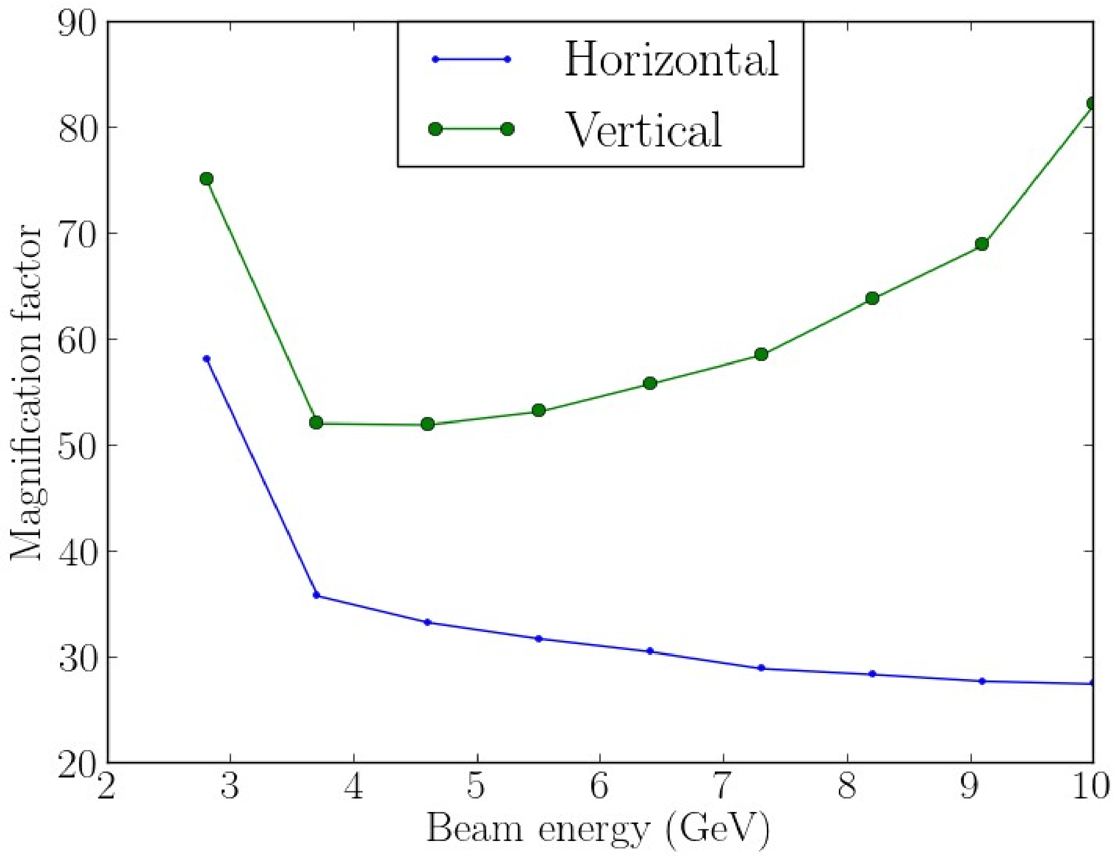
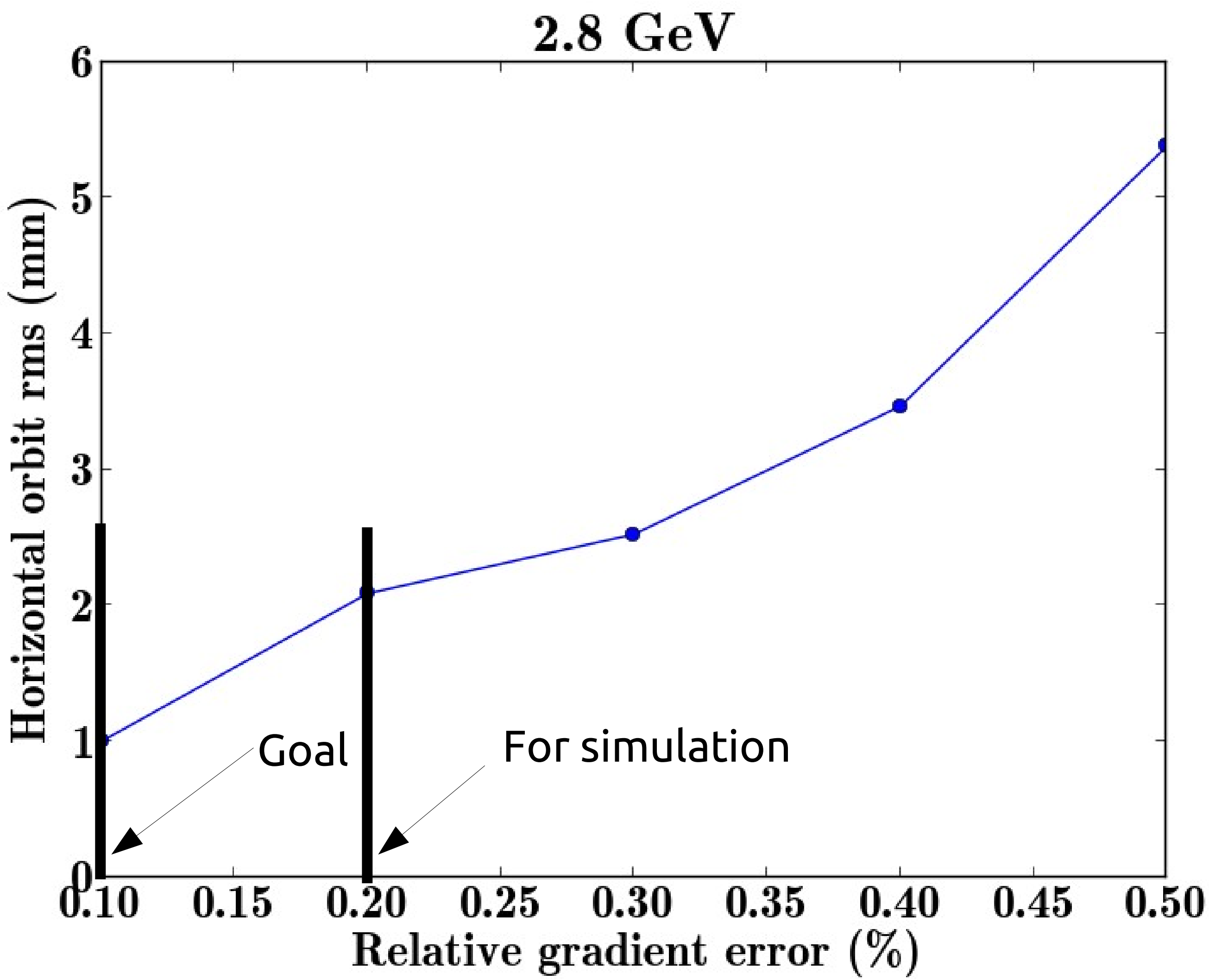
Magnification factor = (Orbit distortion rms)/(Misalignment rms)



➔Magnification factors are in a reasonable range
➔Simulation agree with theoretical approximation

Orbit distortion due to gradient error



Remarks

1. Field error due to misalignment is dB = G*dx, the same for all passes

2. Field error due to gradient error is dB = dG*x, is different for all passes

3. Should disentangle gradient error from misalignment, compensate gradient error by trim quads, and misalignment by dipole correctors

4. Both errors will be corrected at each and every magnet locally

Orbit correction

Correction algorithm

$$\Delta Y = (Y_0 - Y) = R * \theta$$

Y_o is the target orbit, Y is the measured orbit, R is the reponse matrix, θ is the correction strength

Extension to multipass correction,

$$\begin{pmatrix} \Delta Y_1 \\ \vdots \\ \Delta Y_2 \\ \vdots \\ \Delta Y_m \end{pmatrix} = \begin{pmatrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{pmatrix} * \theta$$

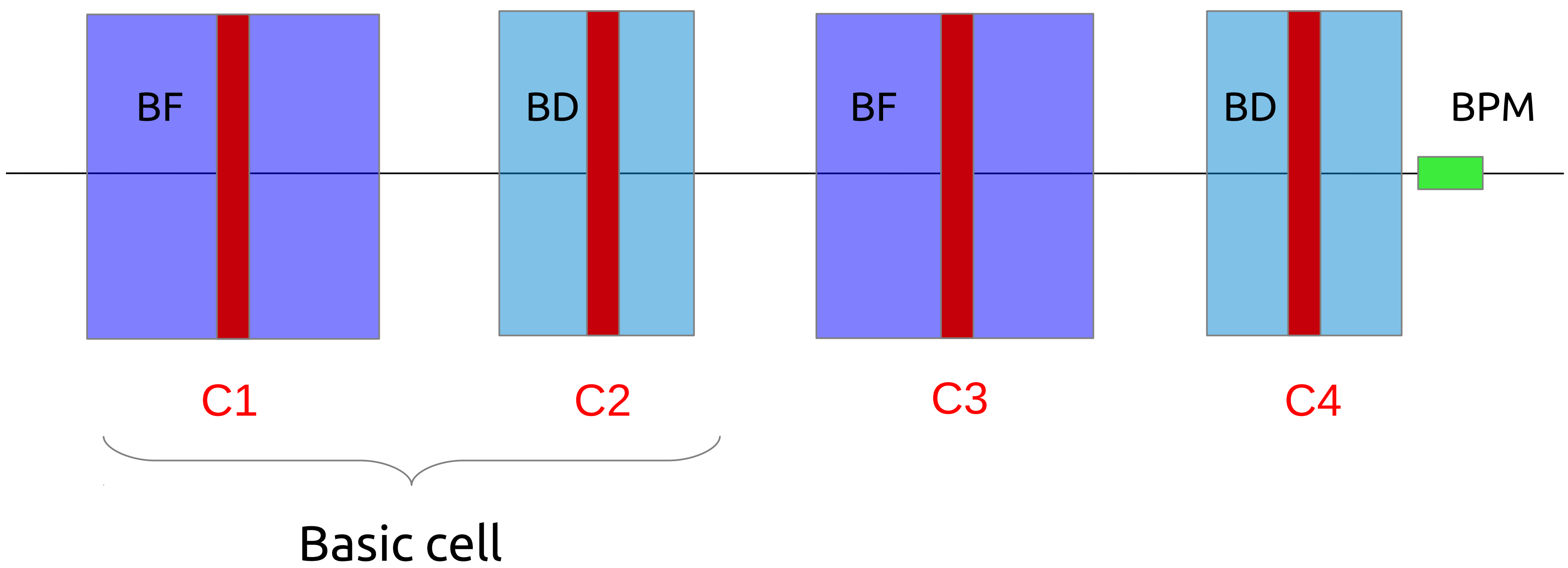
m is number of passes

What's been tested

1. With only misalignment errors and 2 bpms per cell, orbit correction for a single pass, orbit distortions for all passes are reduced under 1 mm peak to peak
2. Correction strengths for different passes are in good agreement, local errors can be found close to perfect
3. Correction scheme was still valid when the misalignment rms error is set to 300 um
4. With 1 bpm per 2 cells, correction for a single pass didn't improve orbits for other passes
5. By varying the Linac energy gain, additional orbits can be acquired (say at 2.7 GeV), correction of this orbit simultaneously with the first pass (at 2.8 GeV) achieves better result

1 BPM 2 cells?

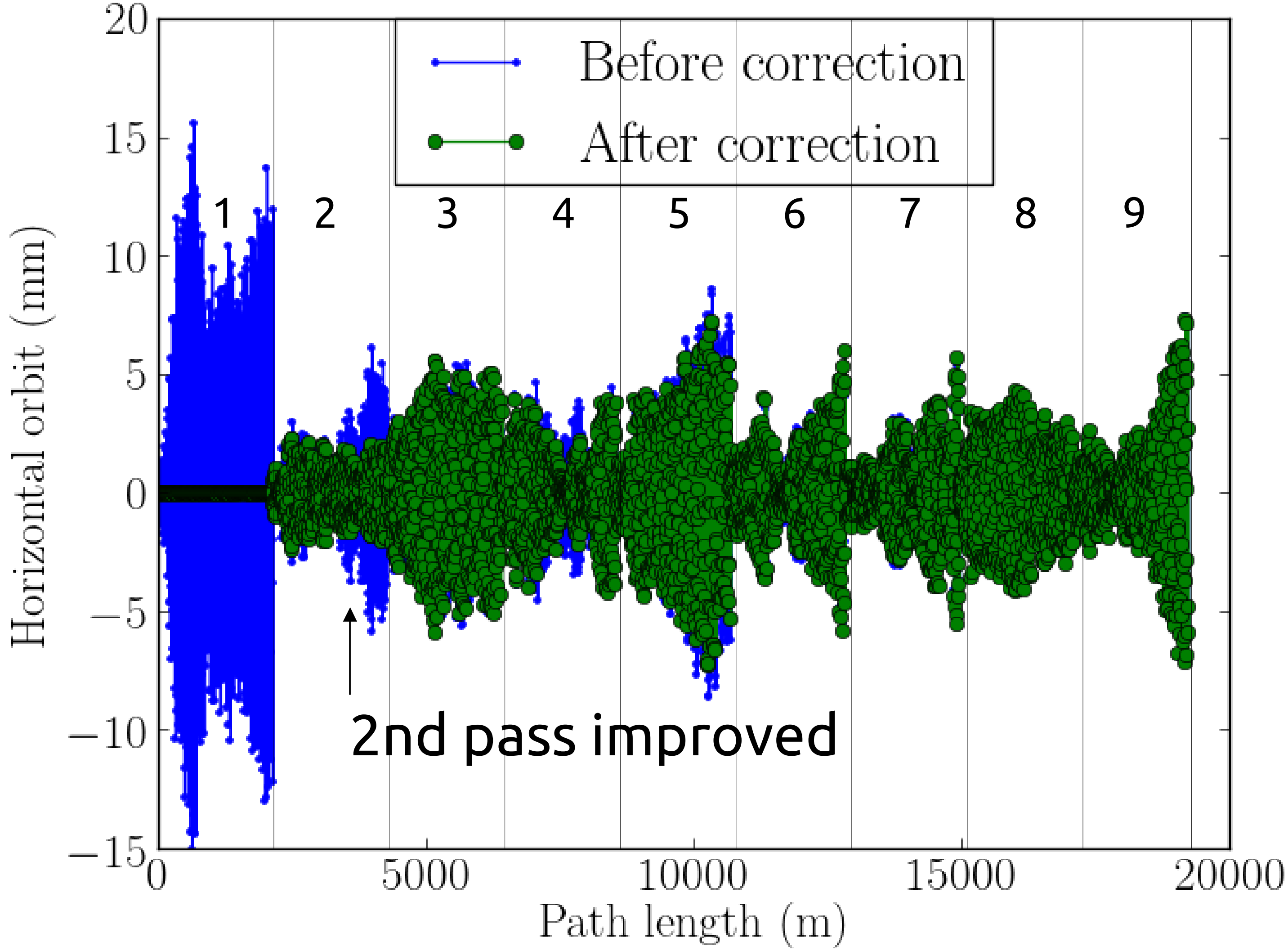
Simulation with 1 bpm/2 cells



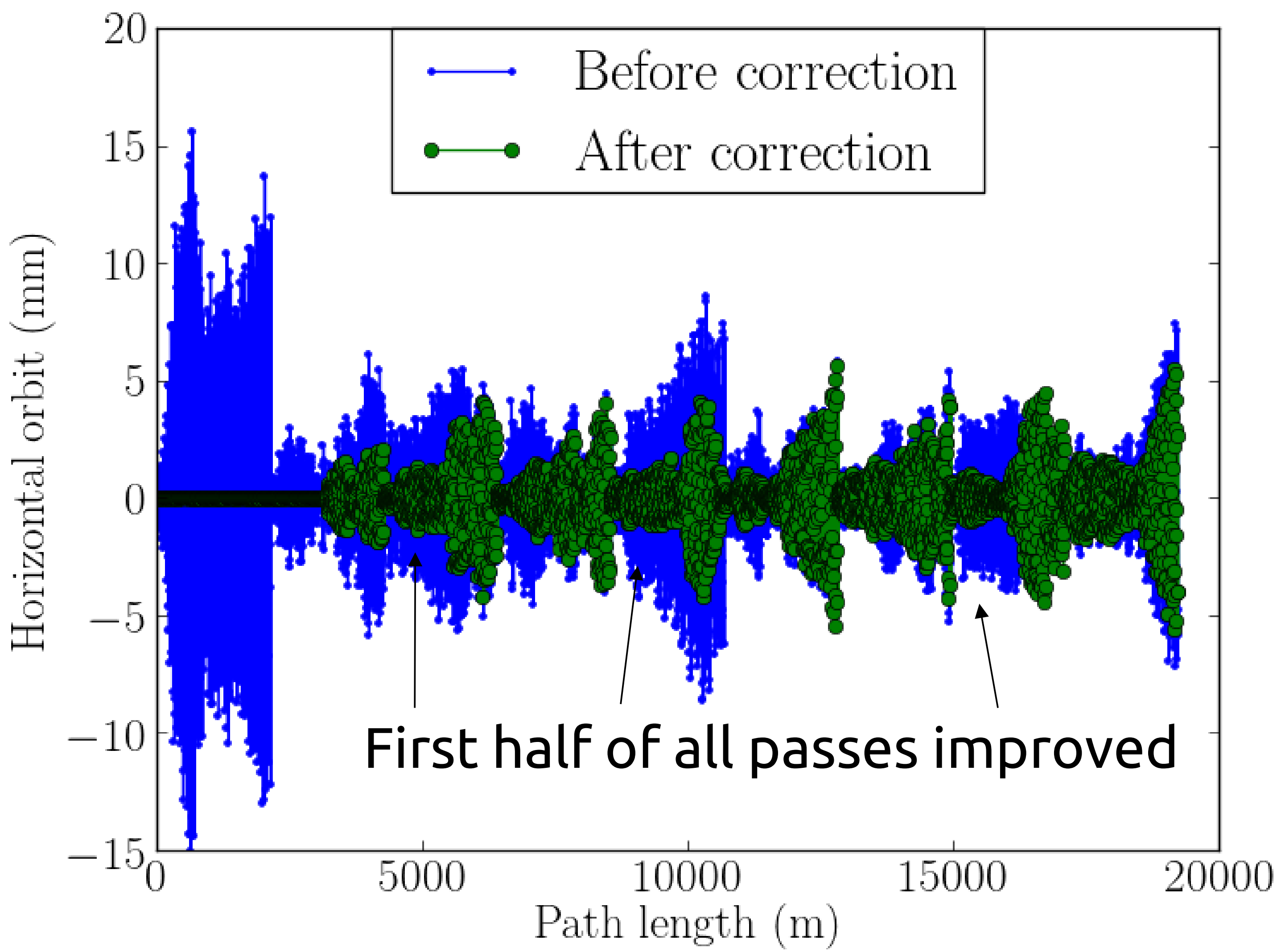
Conditions for simulation

1. 100 um rms misalignment
2. 0.05 mrad rms for roll, pitch, tilt angles
3. Initial errors $\Delta x = 0.5$ mm, $\Delta x' = 0.08$ mrad
4. 0.2% relative gradient error
5. random error in [-20, 20] um for BPM measurements

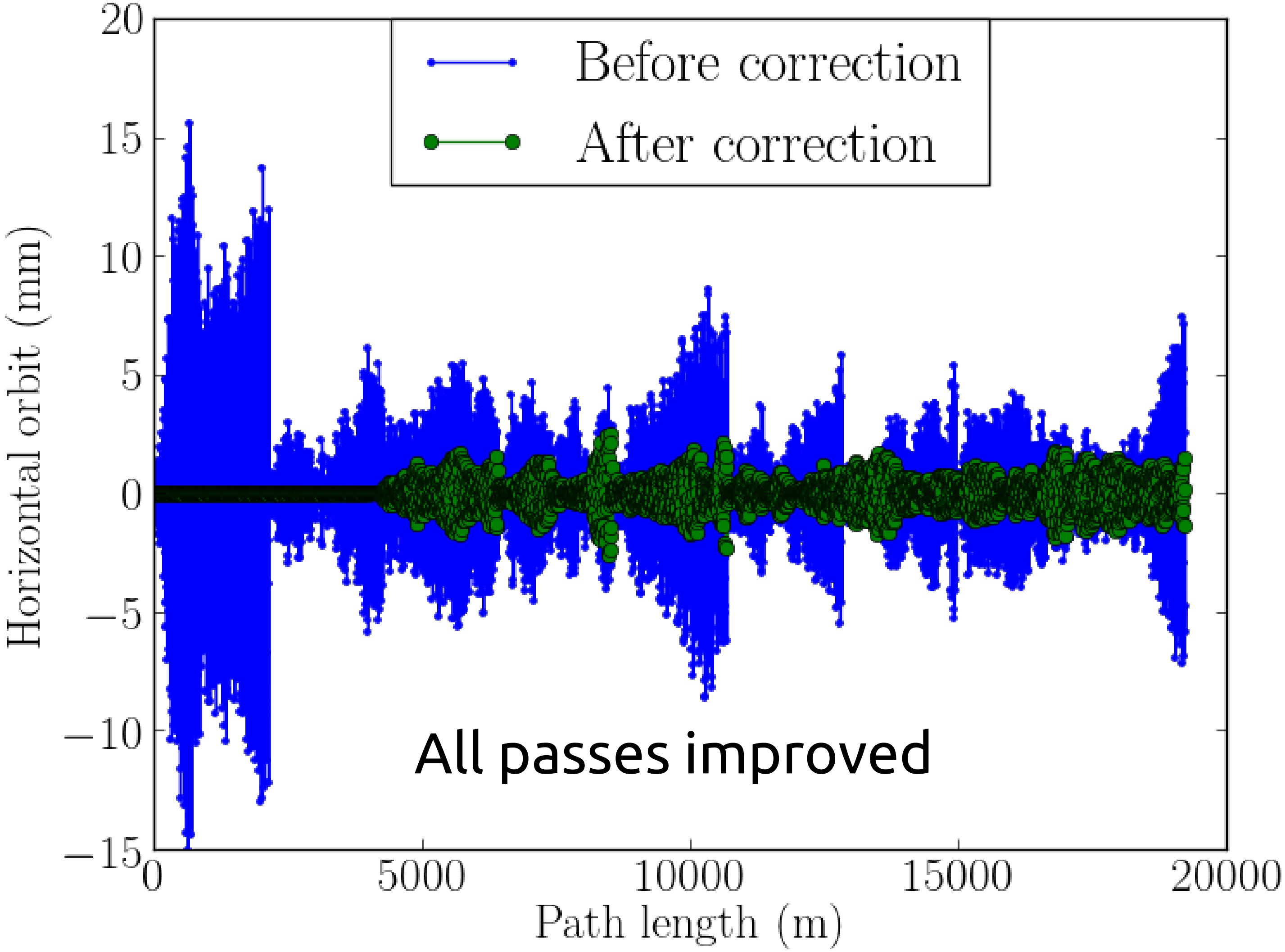
Correcting first pass



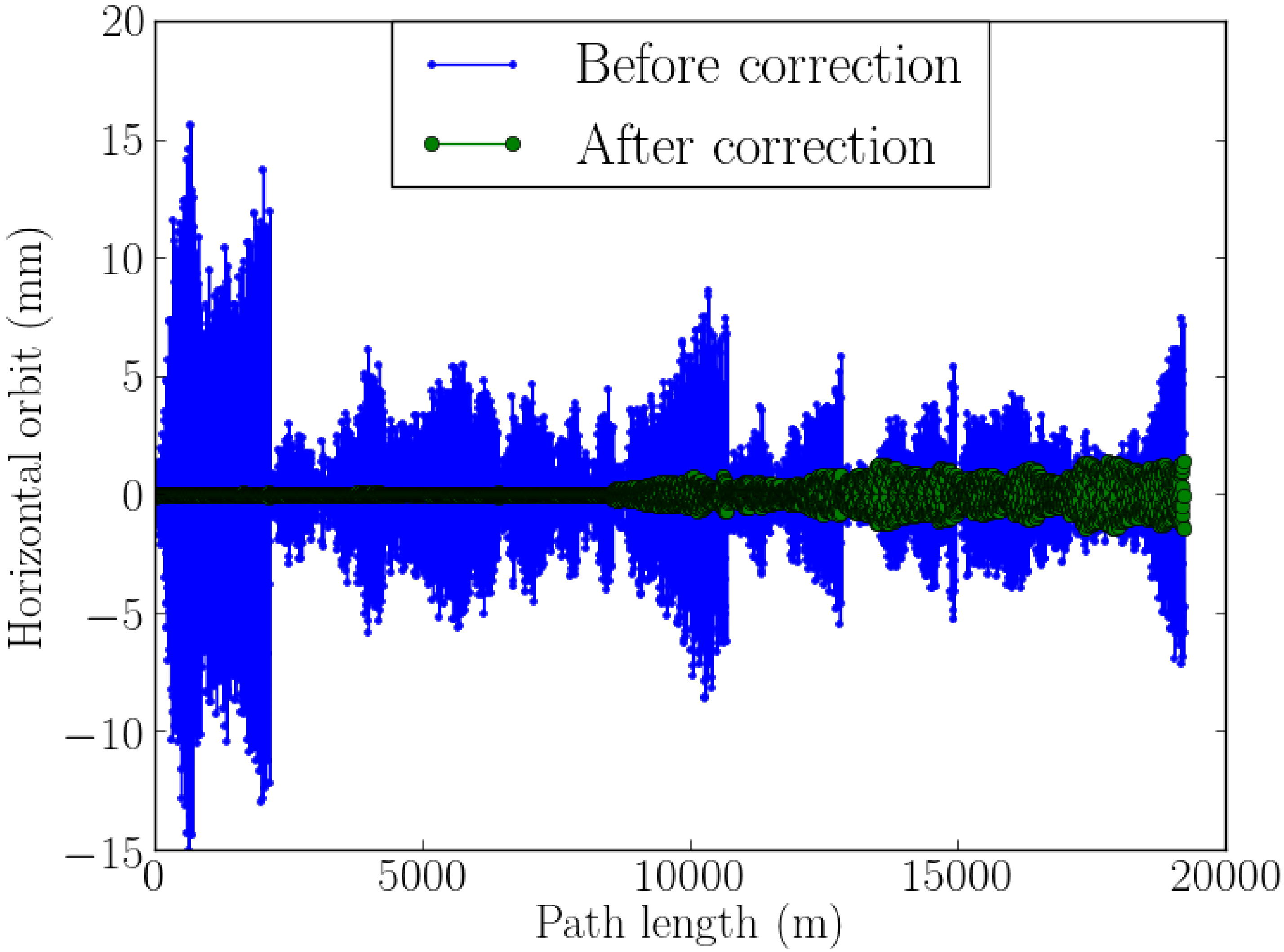
Correcting 1.5 passes



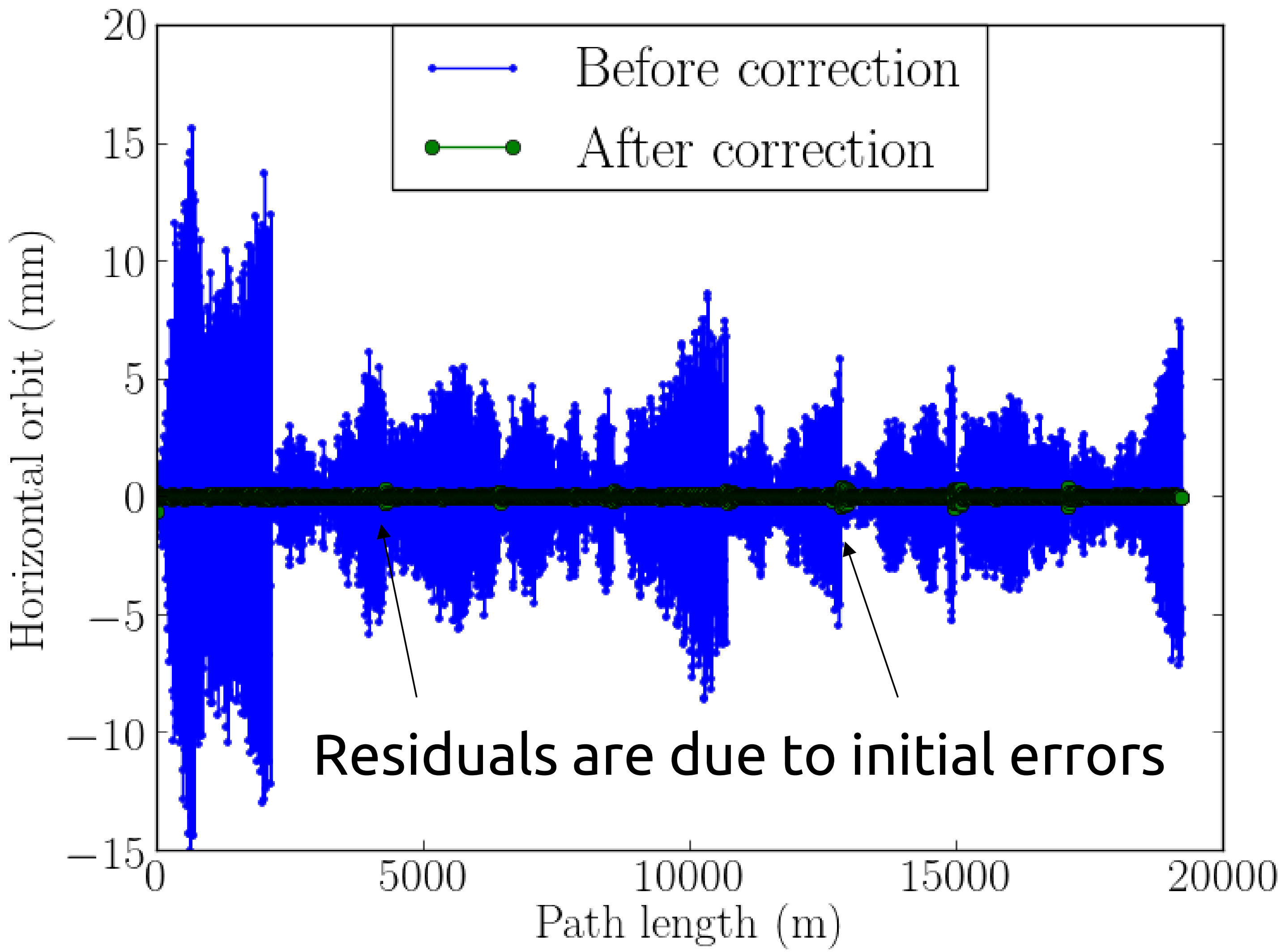
Correcting two passes



Correcting four passes



Correcting nine passes



Gradient error correction

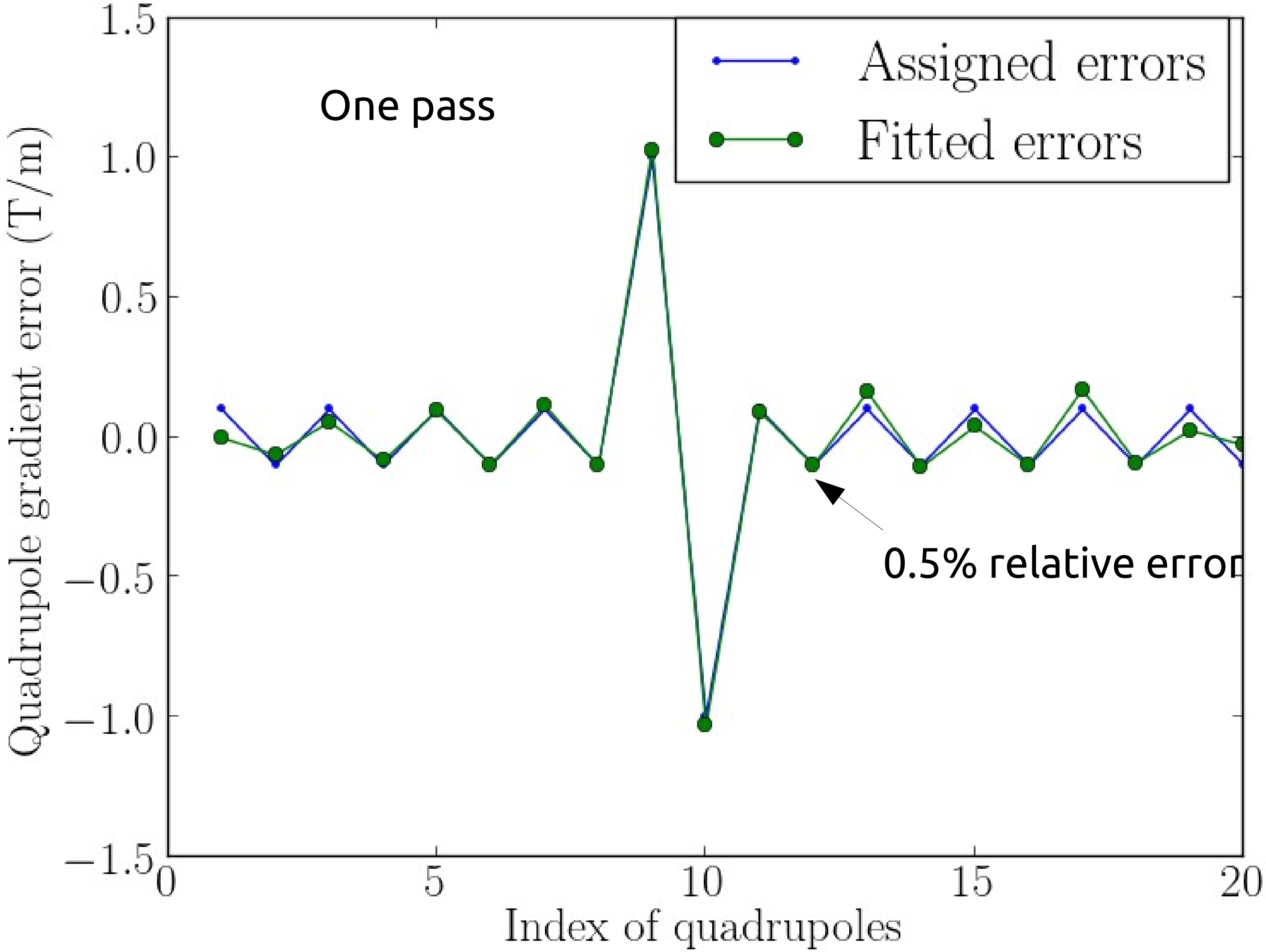
Principles

1. In linear FFAG, orbit response deviation depends only on gradient errors LINEARLY
2. Orbit response deviation from the model can be measured by varying dipole correctors and recording orbits before and after
3. The gradient errors can be fitted with knowledge of the model

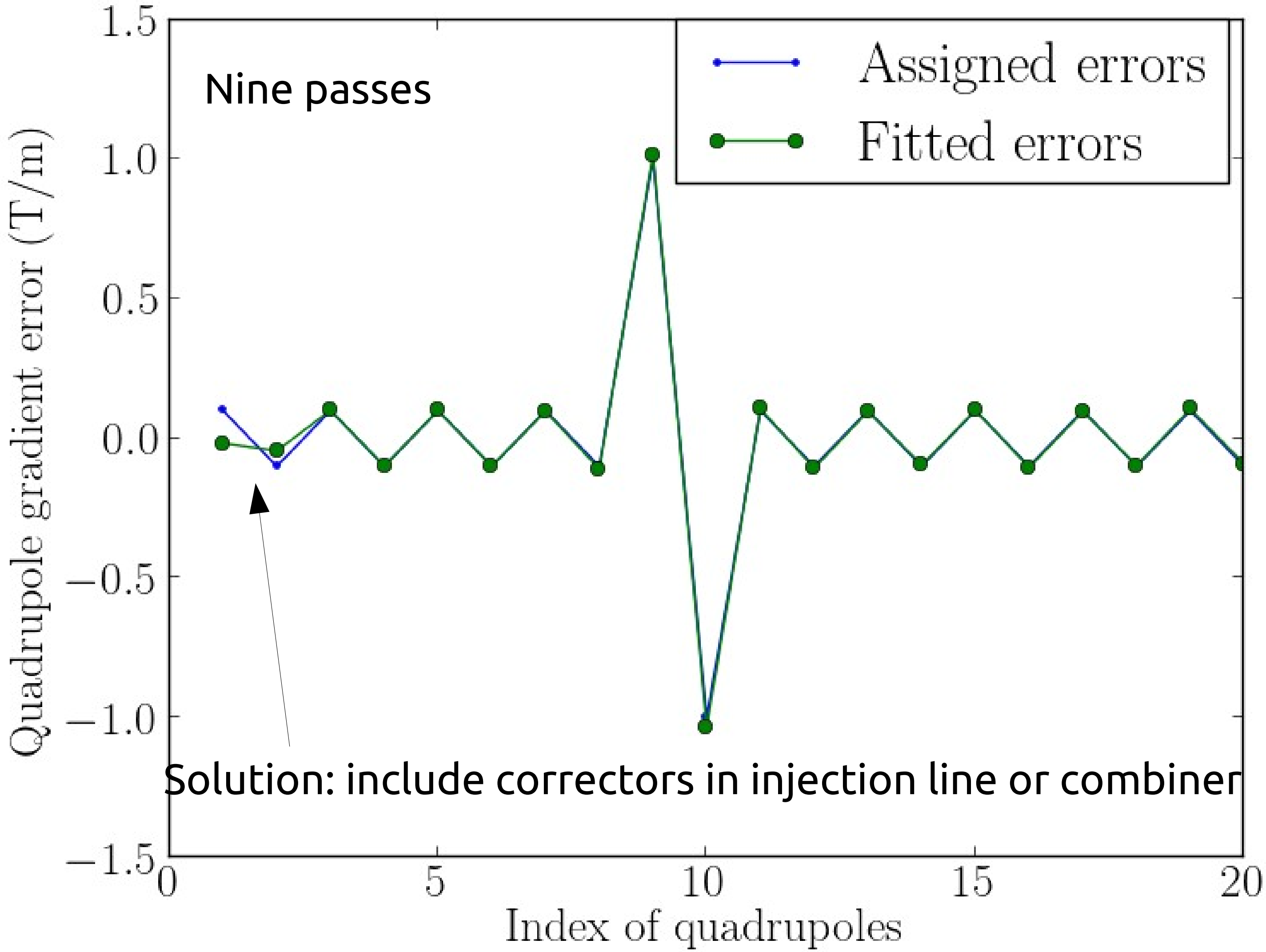
About simulation

1. LOCO-style program in python
2. Simulation were done with 10 basic cells, 20 correctors, and 20 magnets, one BPM per 2 cells
3. Only assigned gradient errors, no calibration or coupling errors
4. Program can be extended to include coupling, BPM calibration and so on

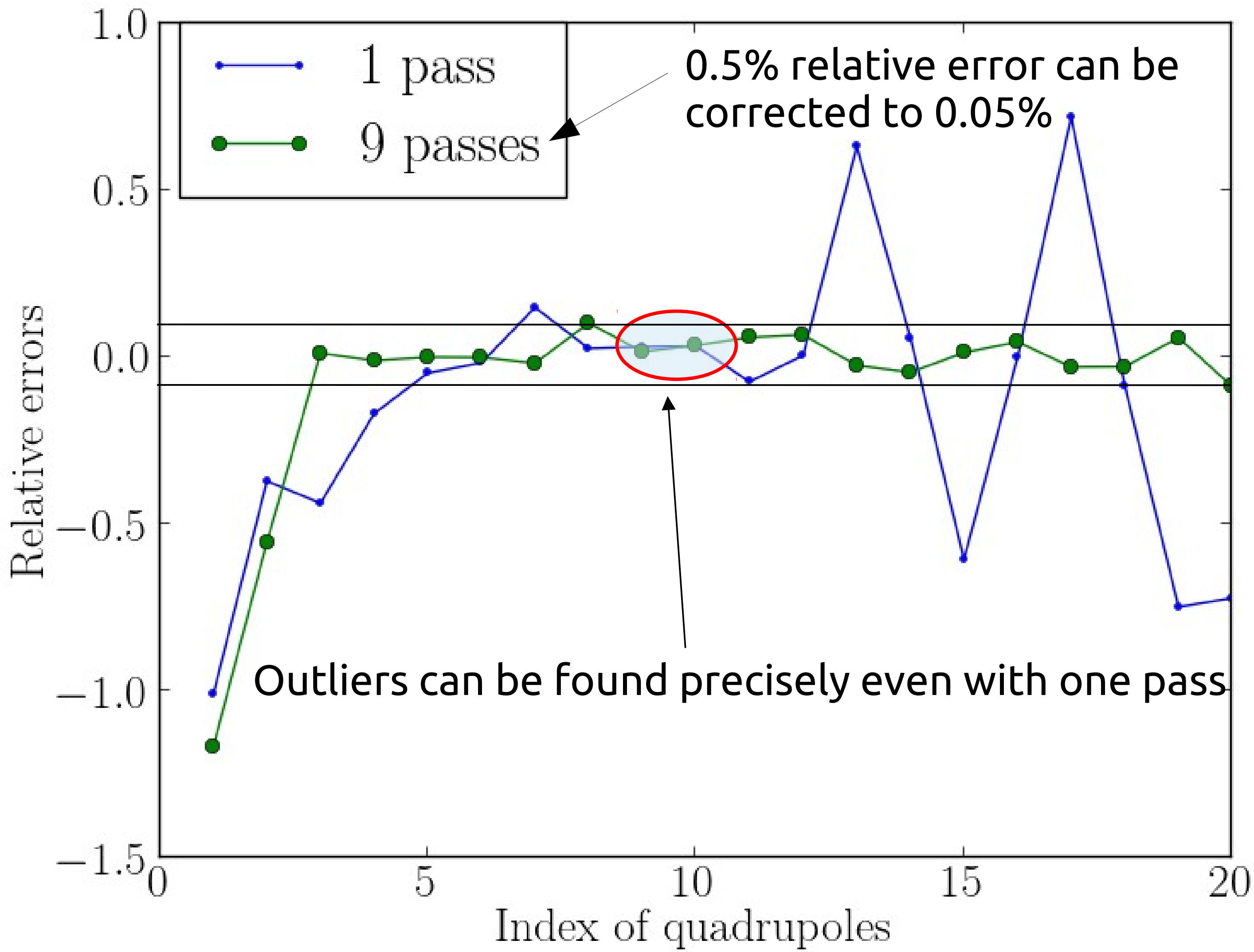
Find known errors



Find known errors



Relative error



OVERALL PLAN

1. Thread beam through the first pass with First turn SVD/sliding bump, or till the point beam won't go through
2. Correct the first pass plus whatever is available in the second
3. Get 2 passes, correct them simultaneously, then 4 passes, 9 passes...
4. Iterate orbit and gradient error multi-pass correction whenever needed

Why we can do better?

	EMMA	FFAG eRHIC
H trim dipole	Moving magnets horizontally	Located in magnets
V trim dipole	14 trims away from magnets	Located in magnets
Trim quads	No	Located in magnets
Septum stray field	Yes	No
Fringe field	Strong	Weak
Bending angle	~11.25 deg	~0.43 deg

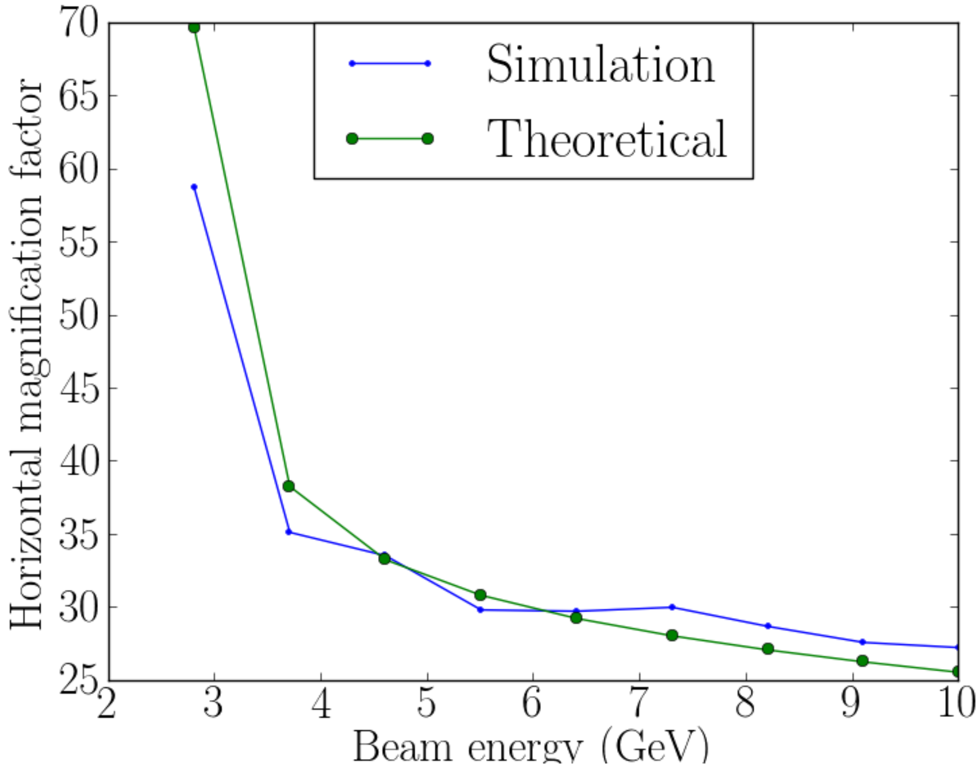
Summary

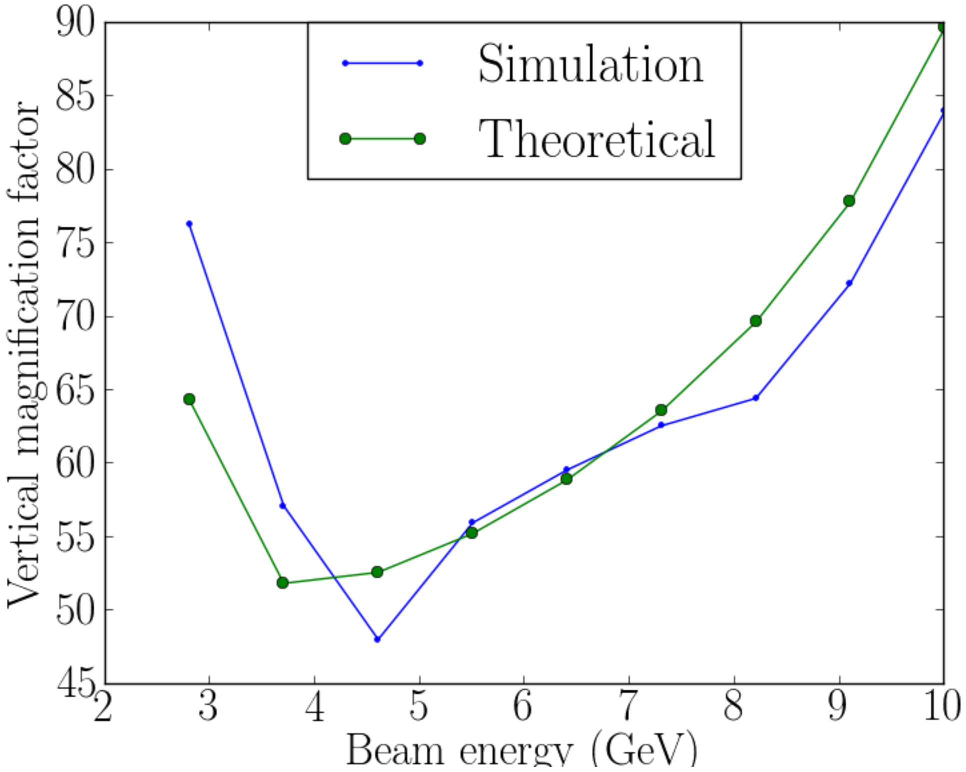
1. Experience of orbit and optics correction at RHIC has been demonstrated
2. Algorithms are prepared to correct both misalignment and gradient errors
3. An overall plan for orbit control was presented

Backups

Cont'd

Magnification factor = (Orbit distortion rms)/(Misalignment rms)

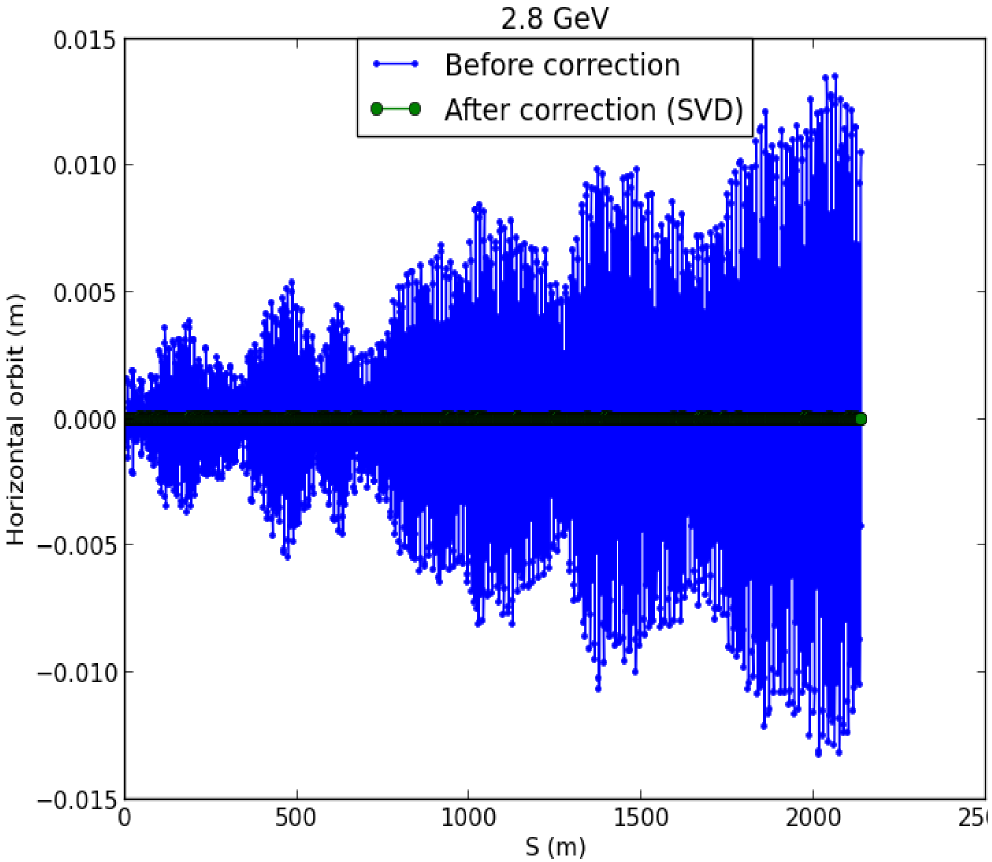




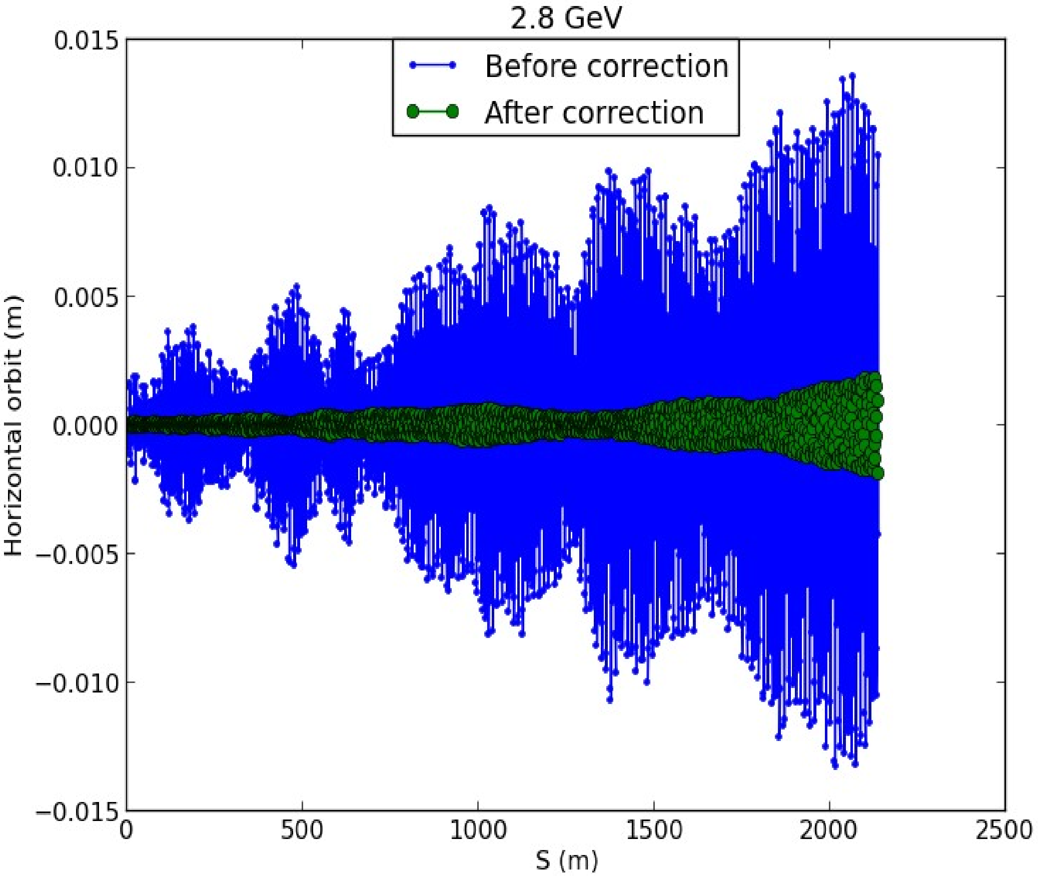
Theoretical magnification factor is proportional to $\sqrt{((\beta\_max + \beta\_min) * \beta\_bpm)} / E$

Orbit correction

Correction based on 2.8 GeV



Correction based on 3.7 GeV



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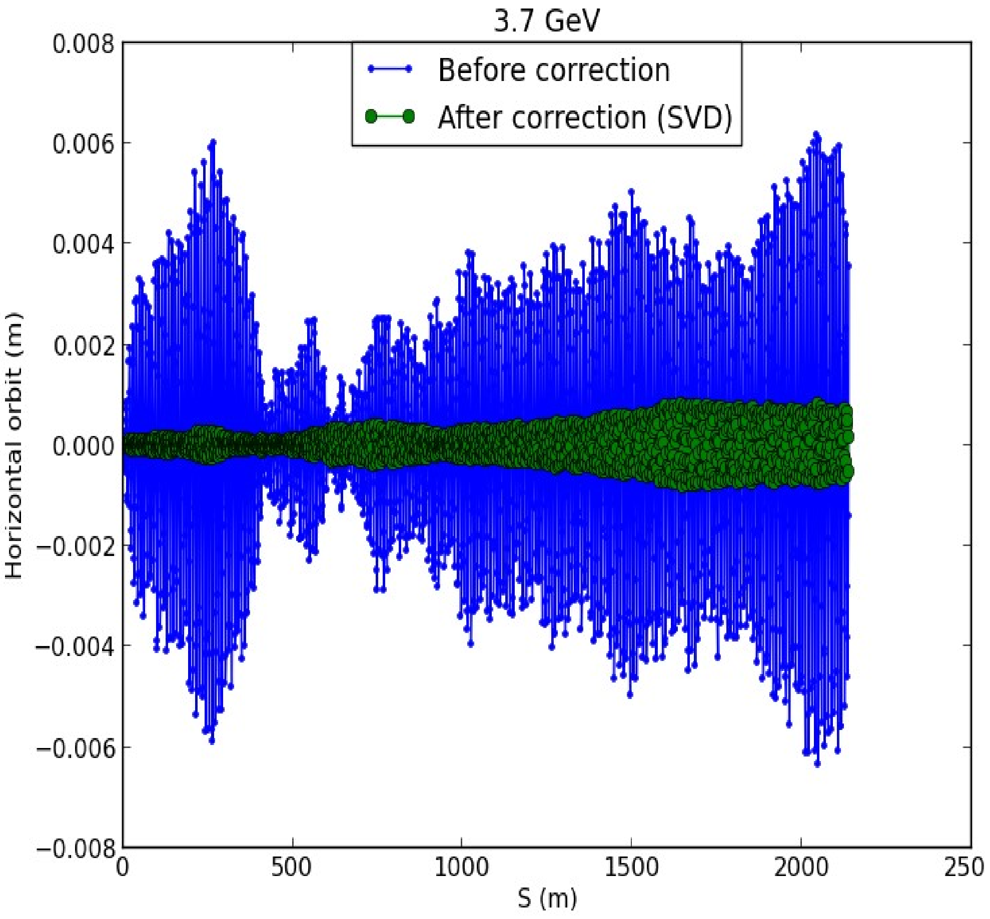
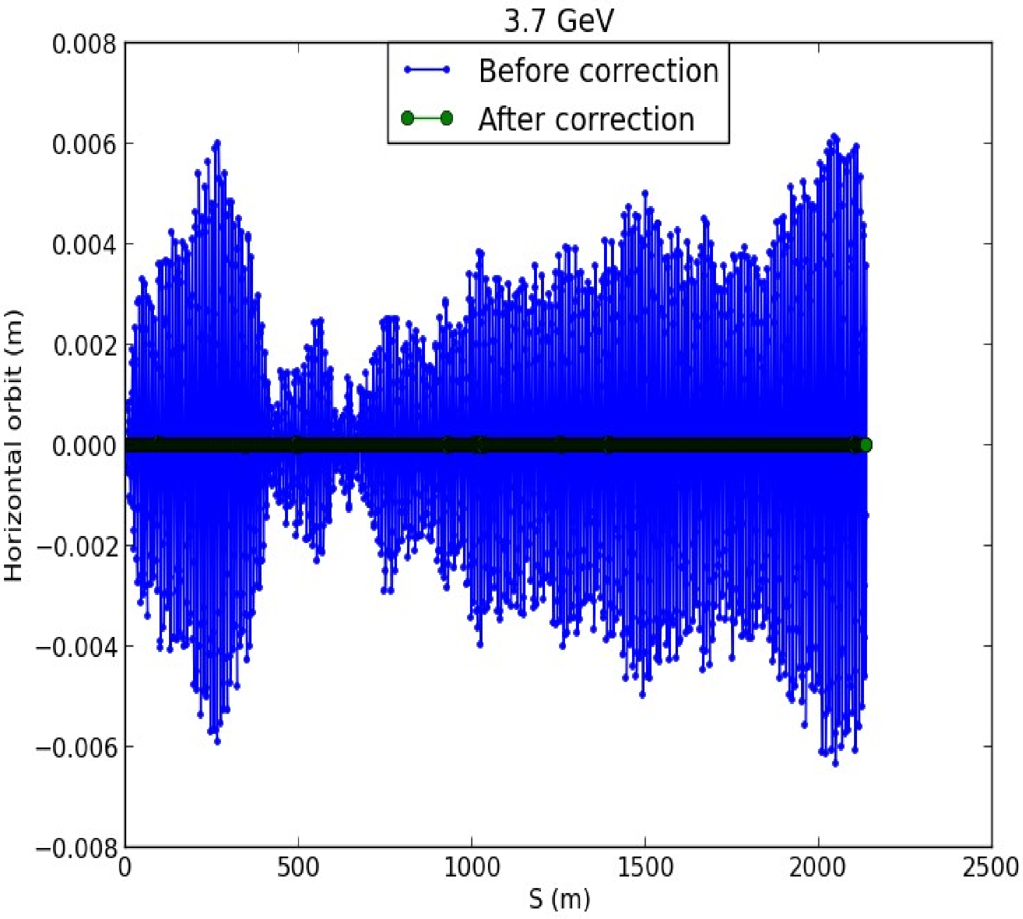
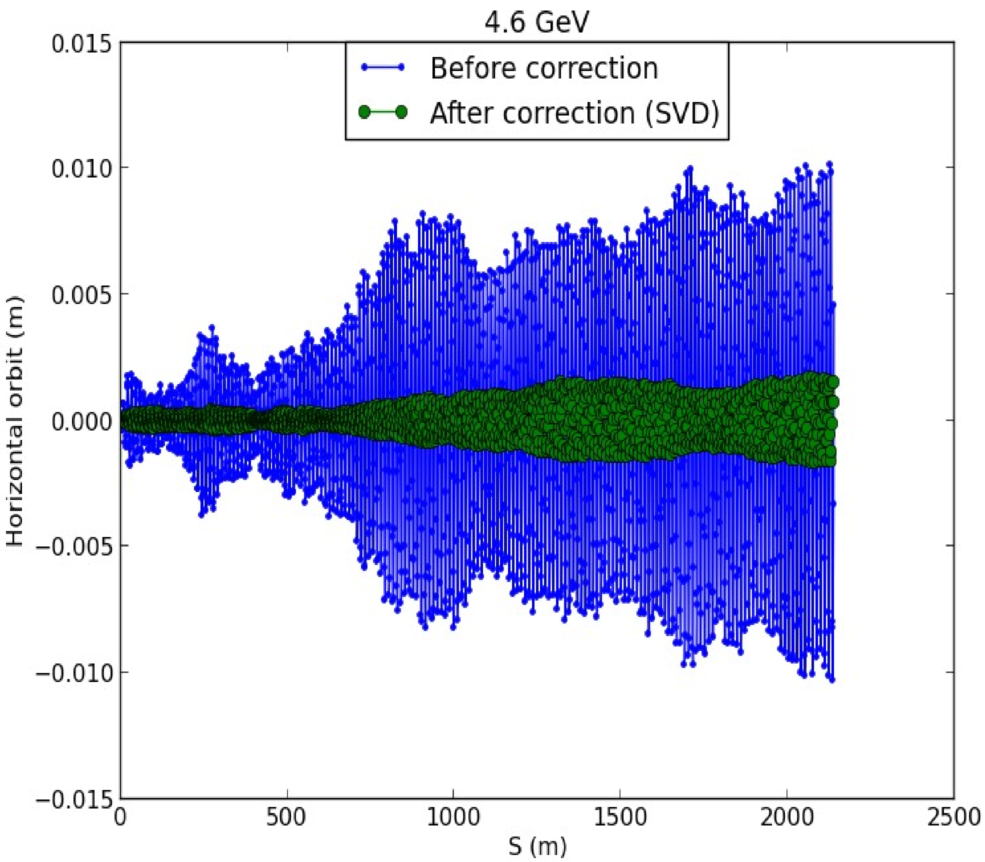
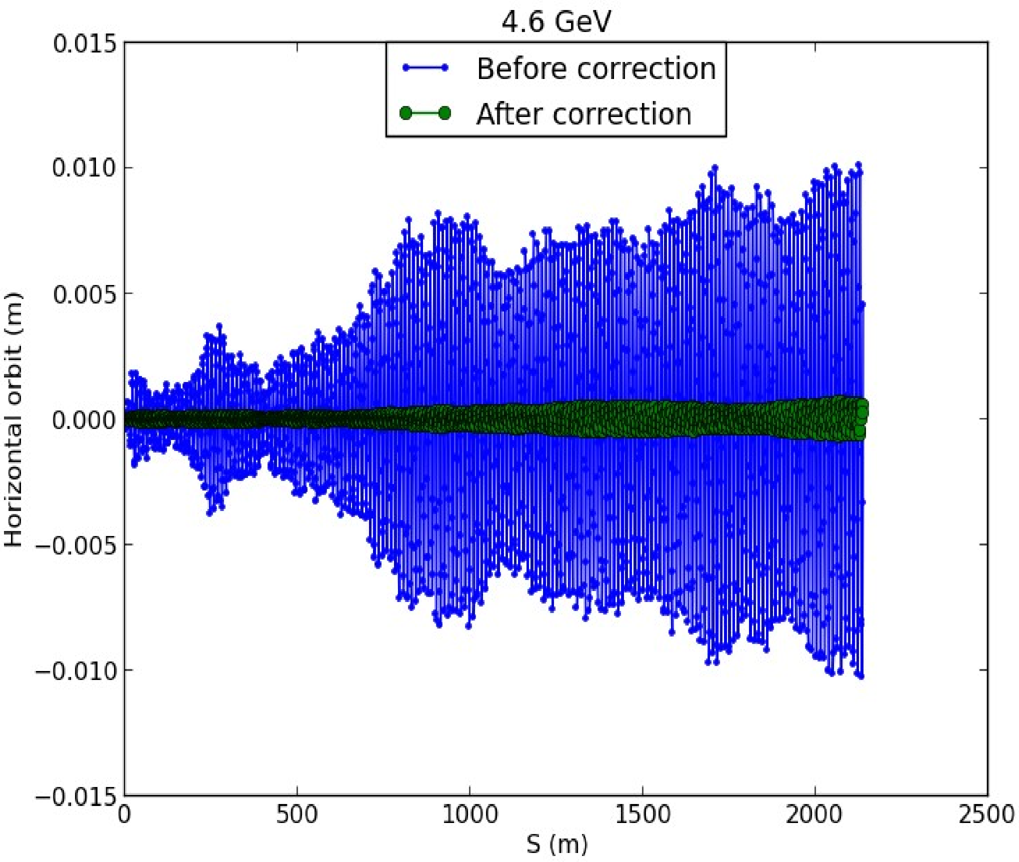

3.7 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
0
500
1000
1500
2000
250

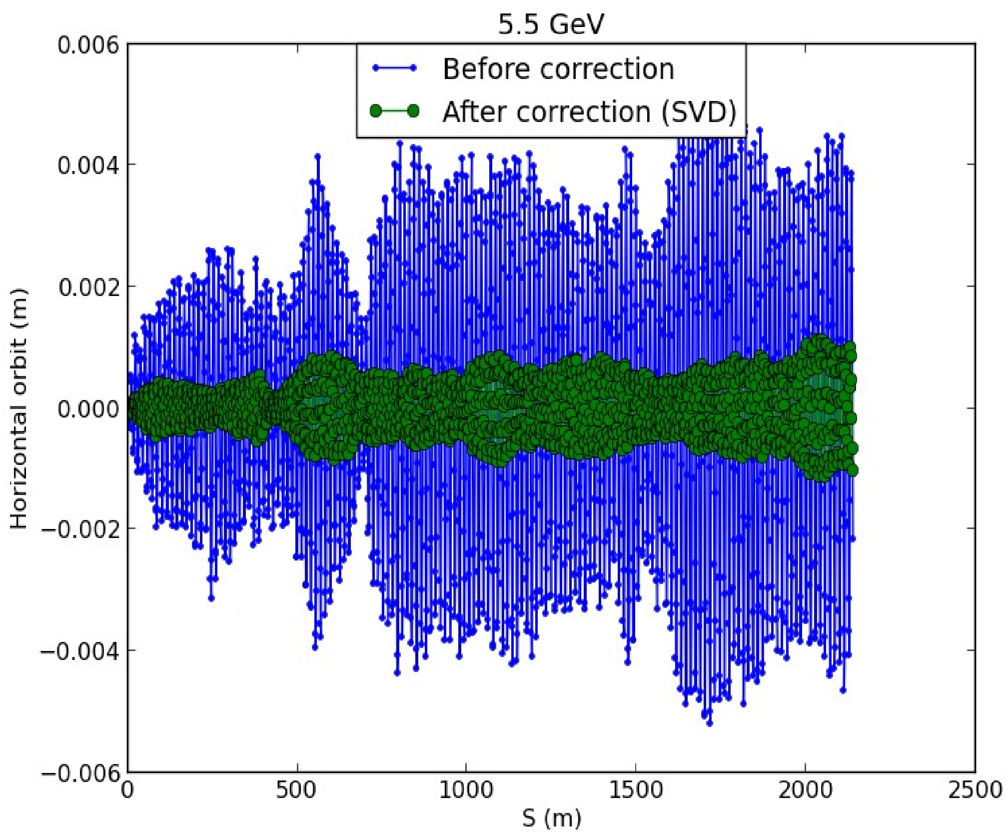

3.7 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
0
500
1000
1500
2000
2500

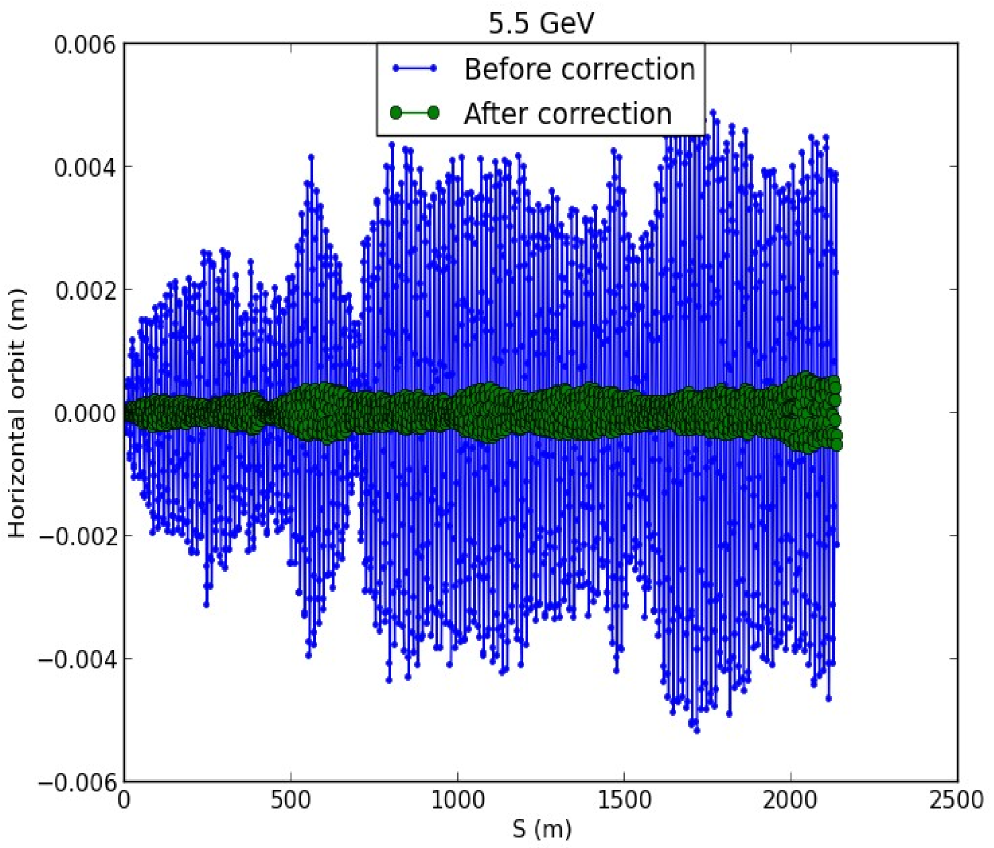
Cont'd


4.6 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
0
500
1000
1500
2000
2500

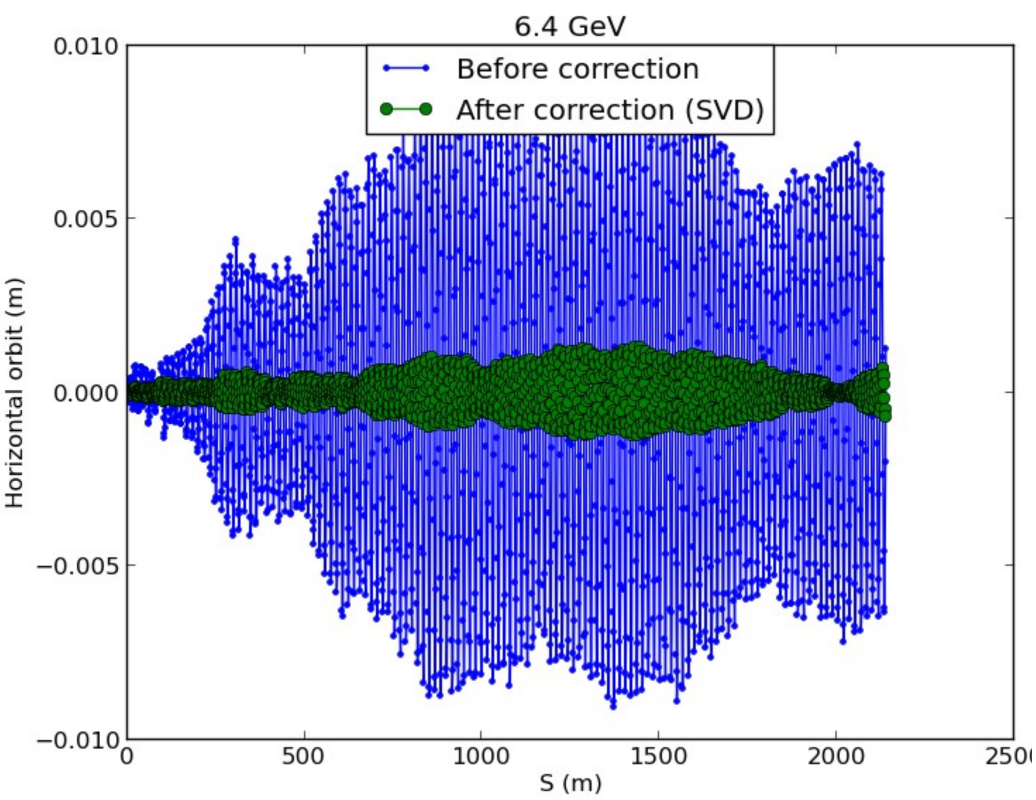

4.6 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
0
500
1000
1500
2000
2500

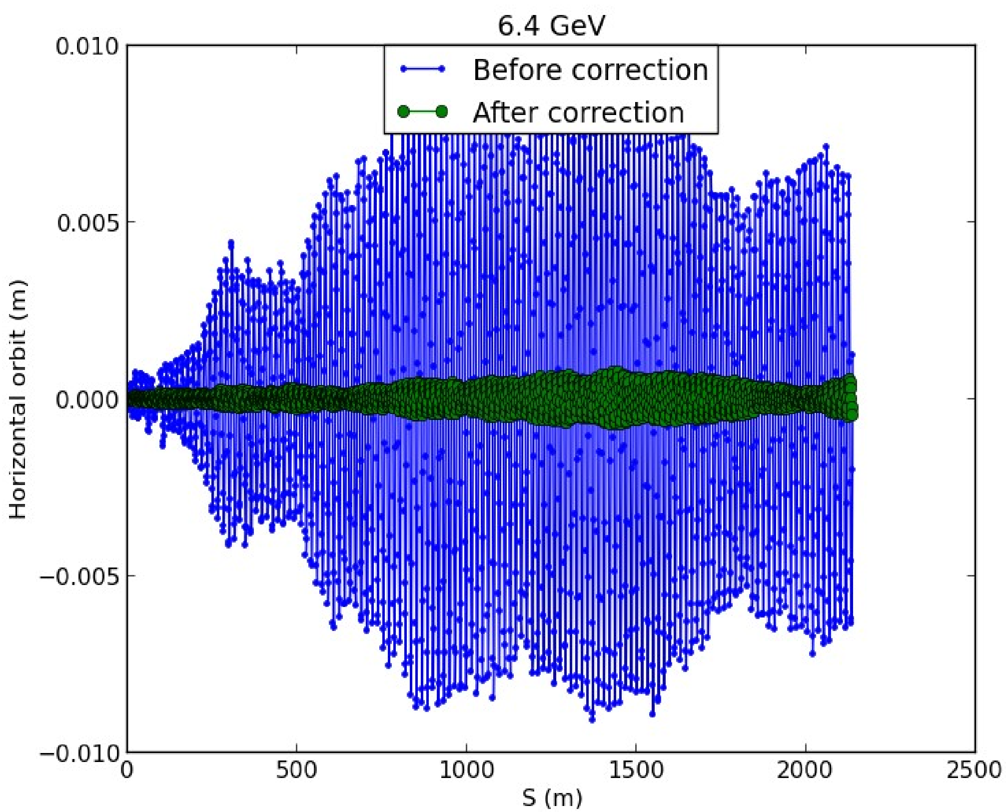
Cont'd


5.5 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
0
500
1000
1500
2000
2500

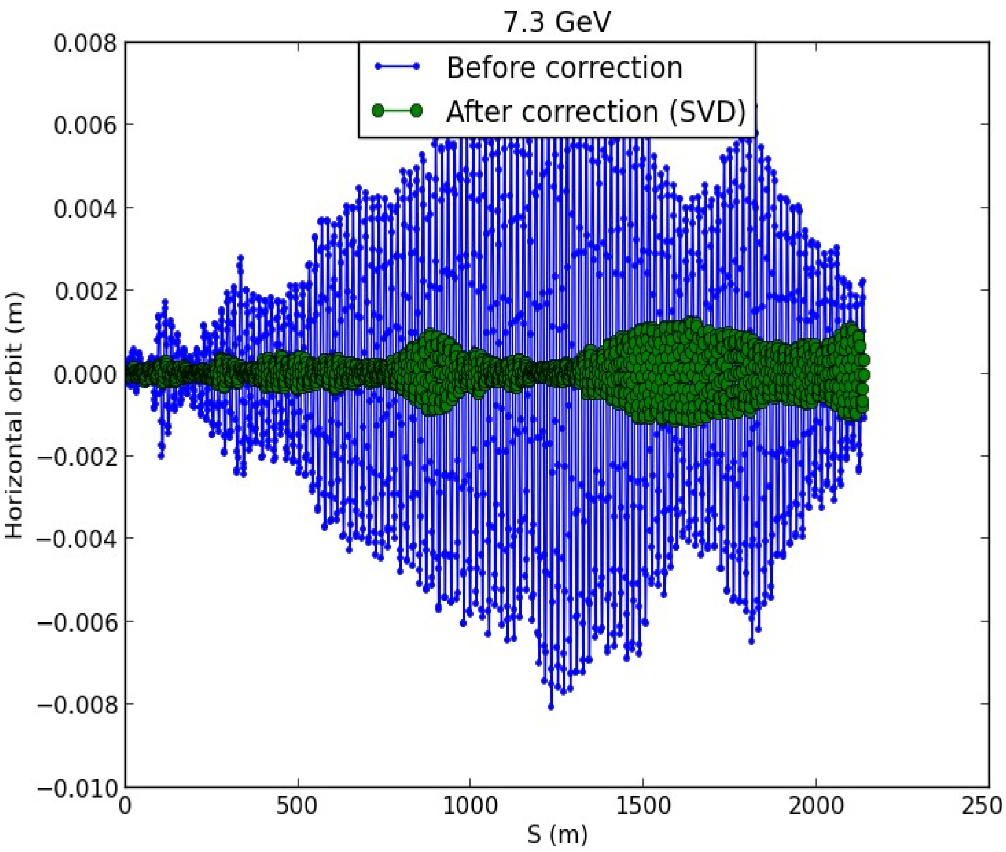

5.5 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
0
500
1000
1500
2000
2500

Cont'd

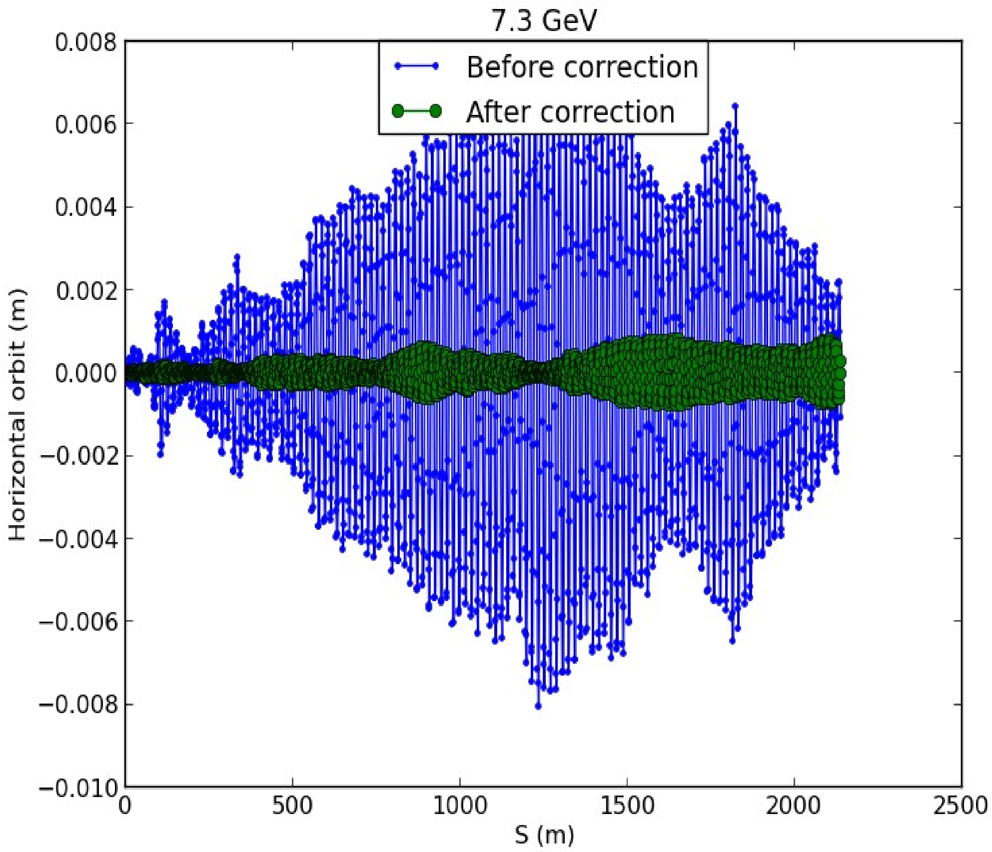

6.4 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.010
0.005
0.000
−0.005
−0.010
0
500
1000
1500
2000
250


6.4 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.010
0.005
0.000
−0.005
−0.010
0
500
1000
1500
2000
2500

Cont'd

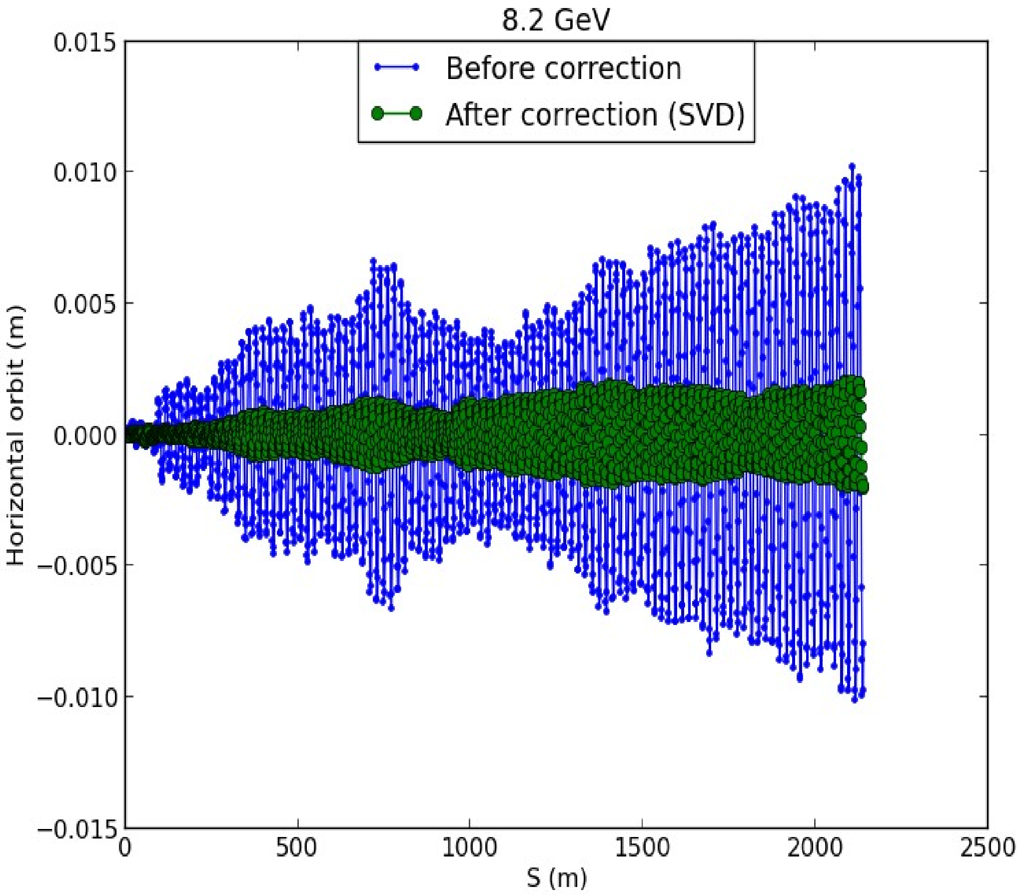


7.3 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
−0.010
0
500
1000
1500
2000
250

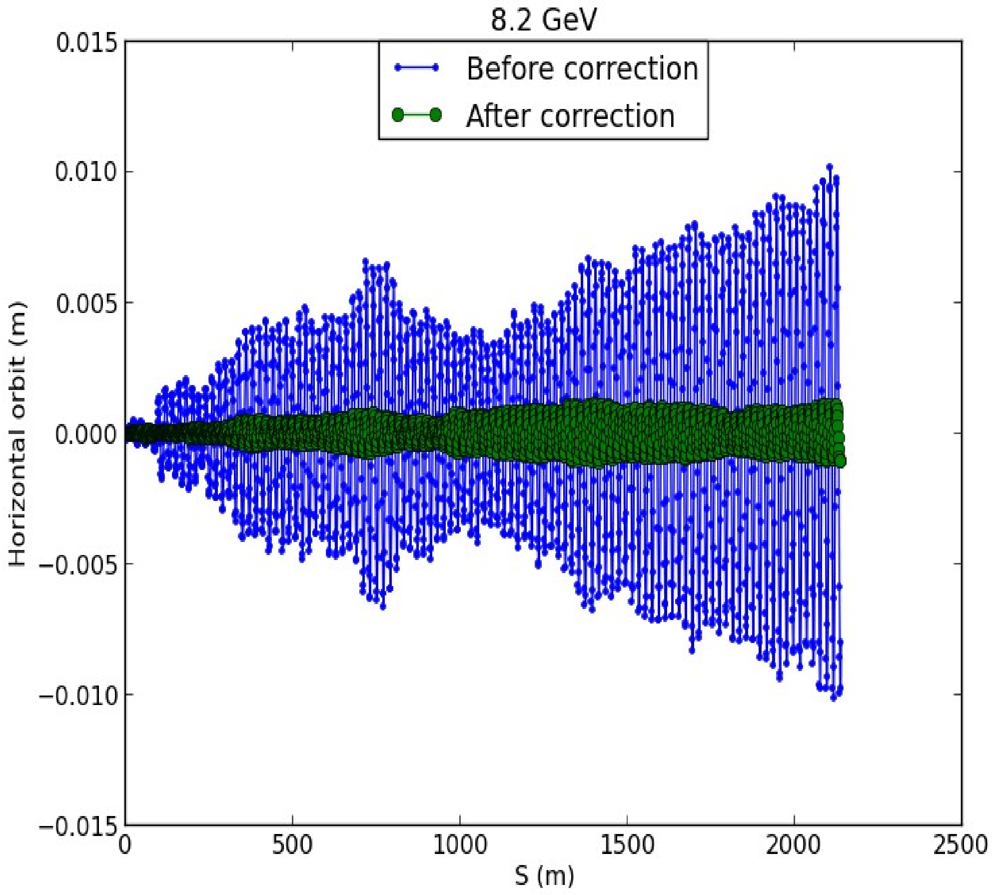


7.3 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
−0.010
0
500
1000
1500
2000
2500

Cont'd

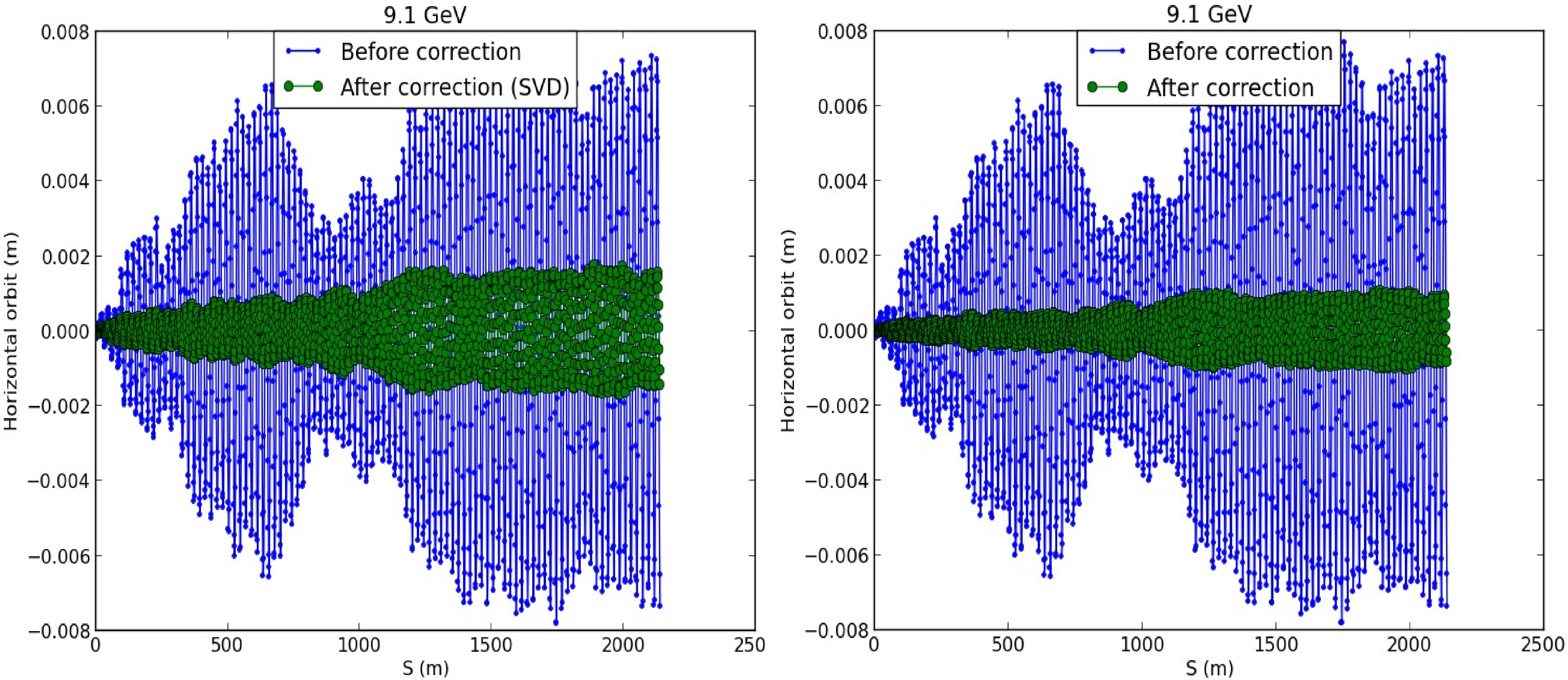


8.2 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
0
500
1000
1500
2000
2500

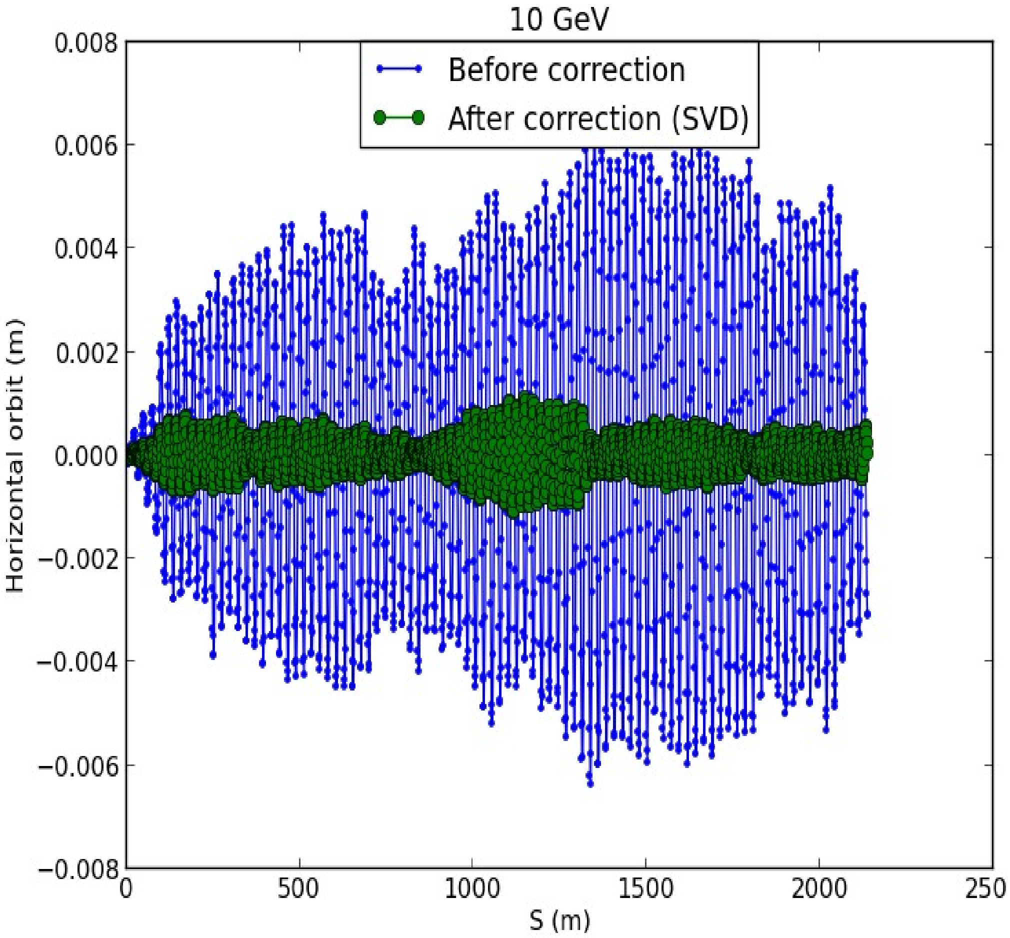


8.2 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
0
500
1000
1500
2000
2500

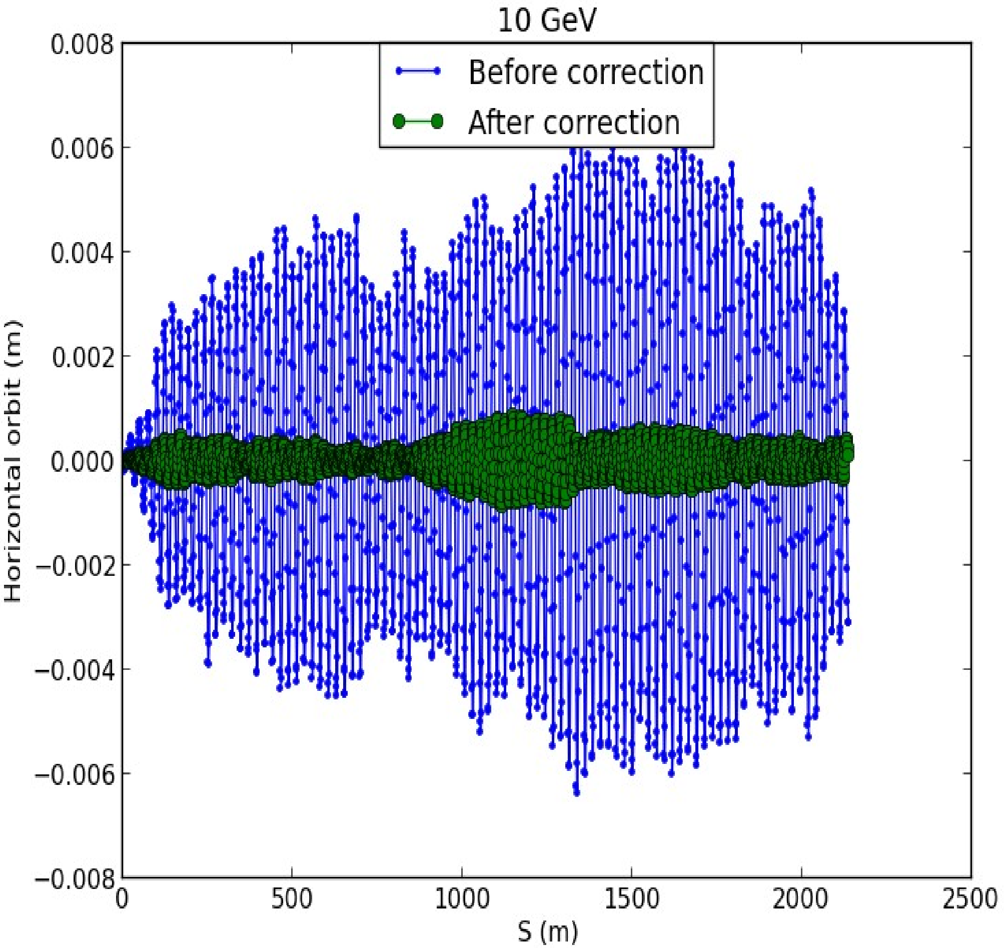
Cont'd


9.1 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
0
500
1000
1500
2000
250
9.1 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
0
500
1000
1500
2000
2500

Cont'd



10 GeV
Before correction
After correction (SVD)
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
0
500
1000
1500
2000
250



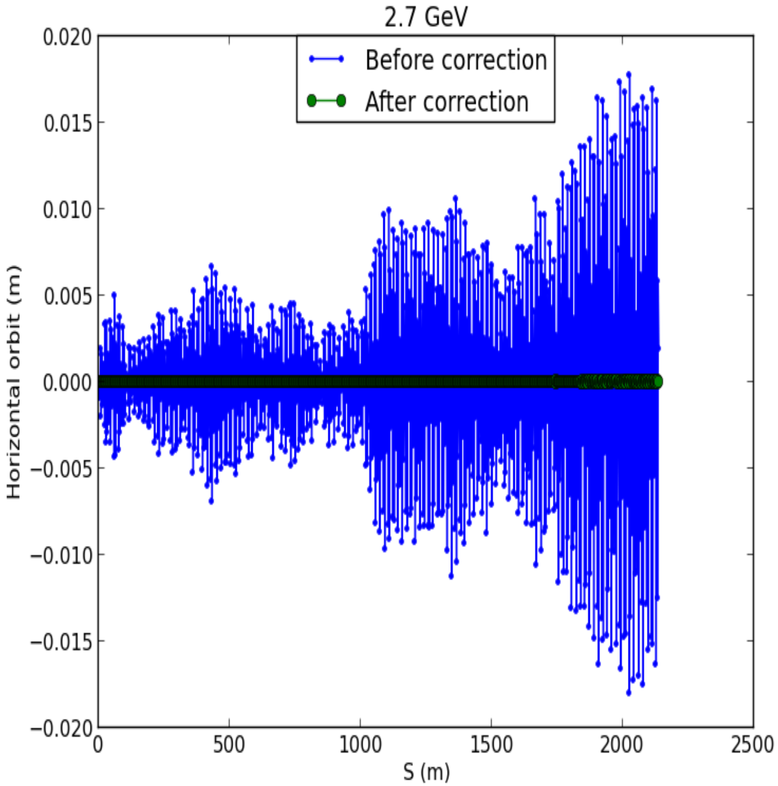
10 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
0
500
1000
1500
2000
2500

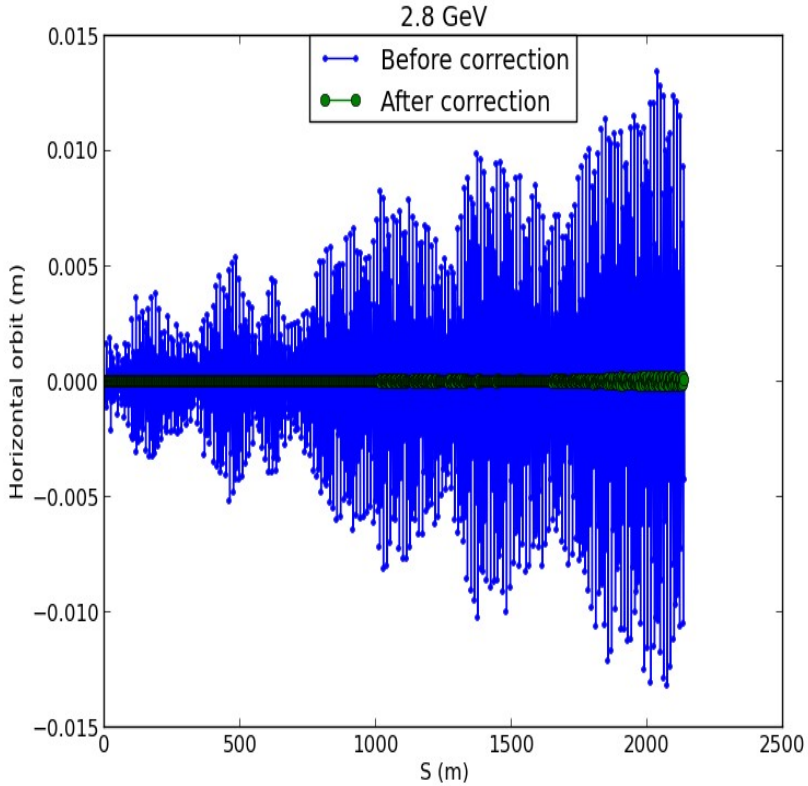
Correcting multi-pass simultaneously?

1. V. Litvinenko suggested orbits from multi-pass can be utilized to reduce the number of BPMs

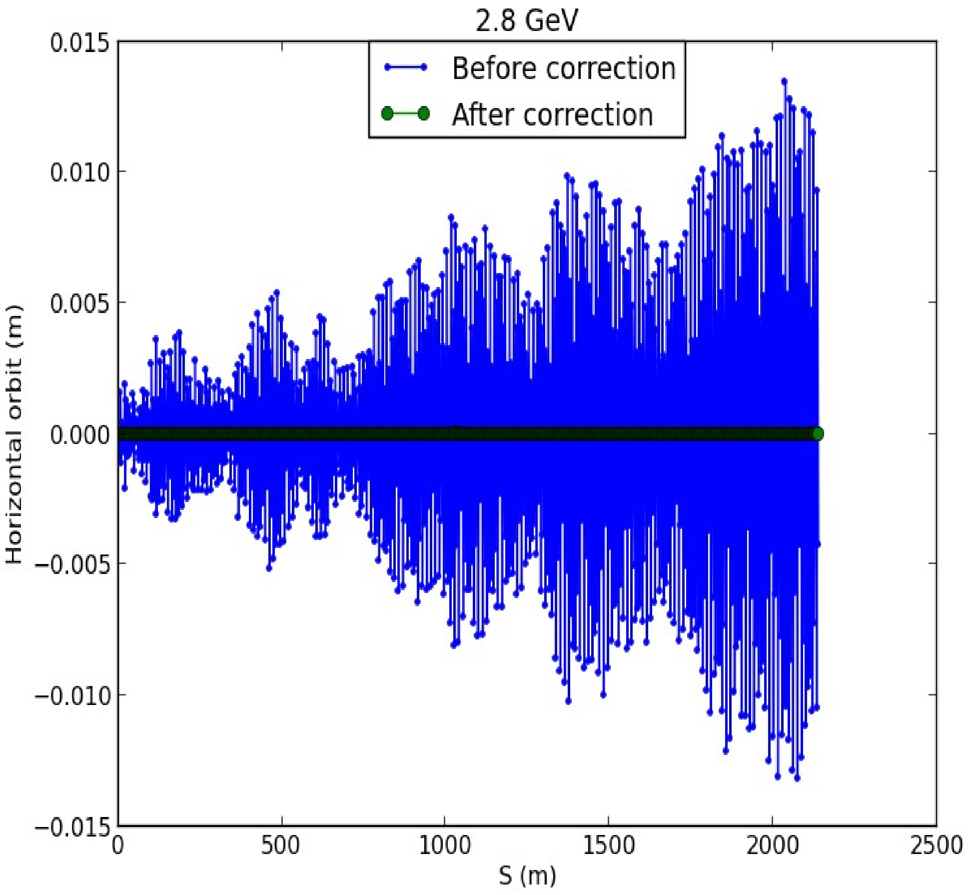
2. I. Ben-Zvi suggested varying beam energy to get multiple orbits, as did in NSLS

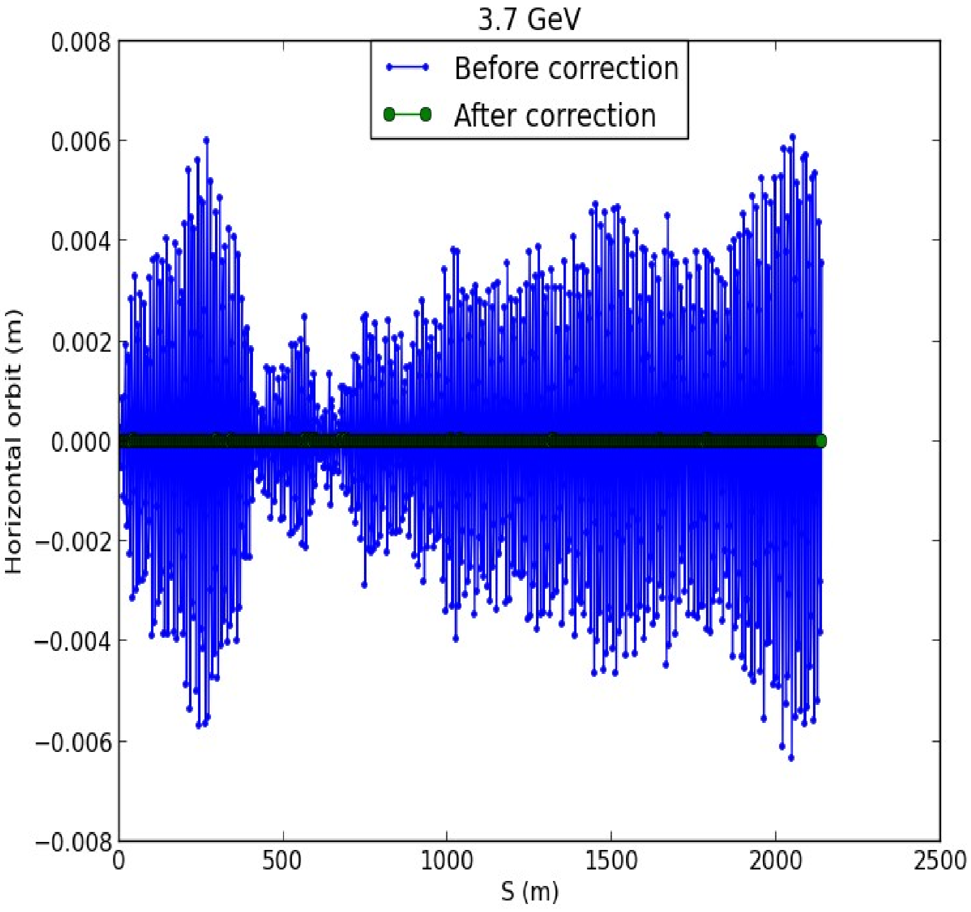
2.7 & 2.8 GeV


2.7 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020
0
500
1000
1500
2000
2500

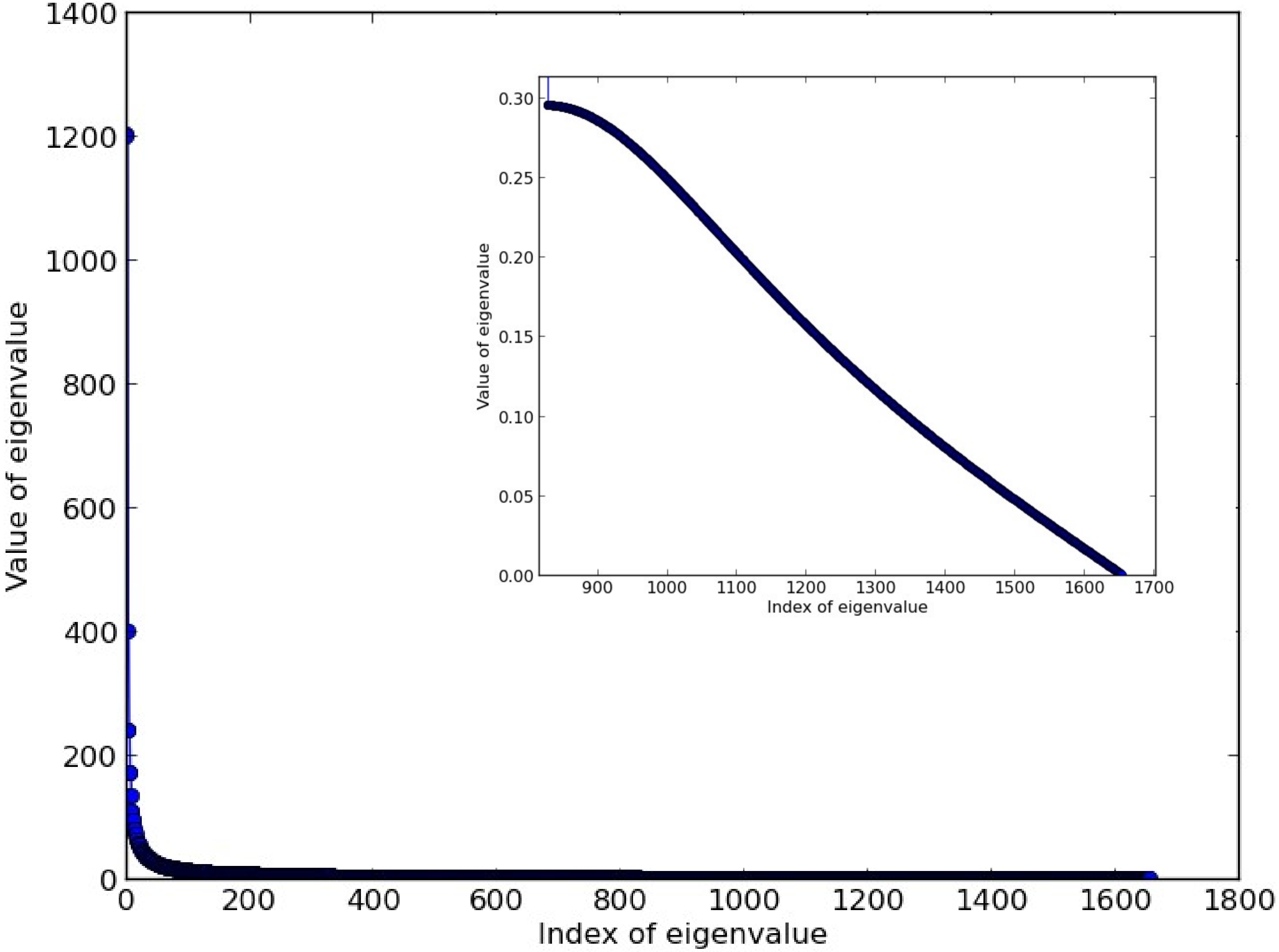

2.8 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
0
500
1000
1500
2000
2500

3.7 & 2.8 GeV

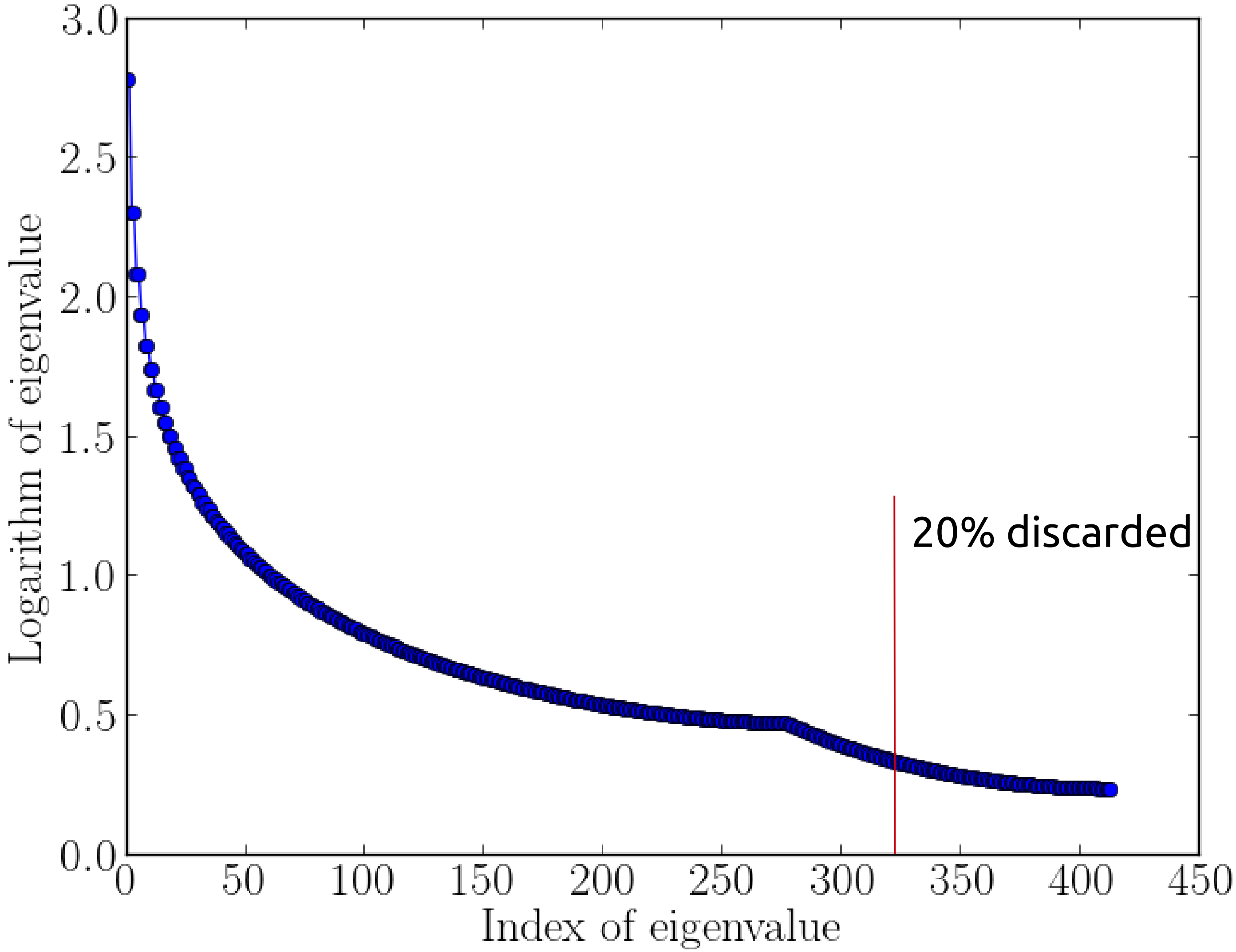

2.8 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
0
500
1000
1500
2000
2500


3.7 GeV
Before correction
After correction
Horizontal orbit (m)
S (m)
0.008
0.006
0.004
0.002
0.000
−0.002
−0.004
−0.006
−0.008
0
500
1000
1500
2000
2500

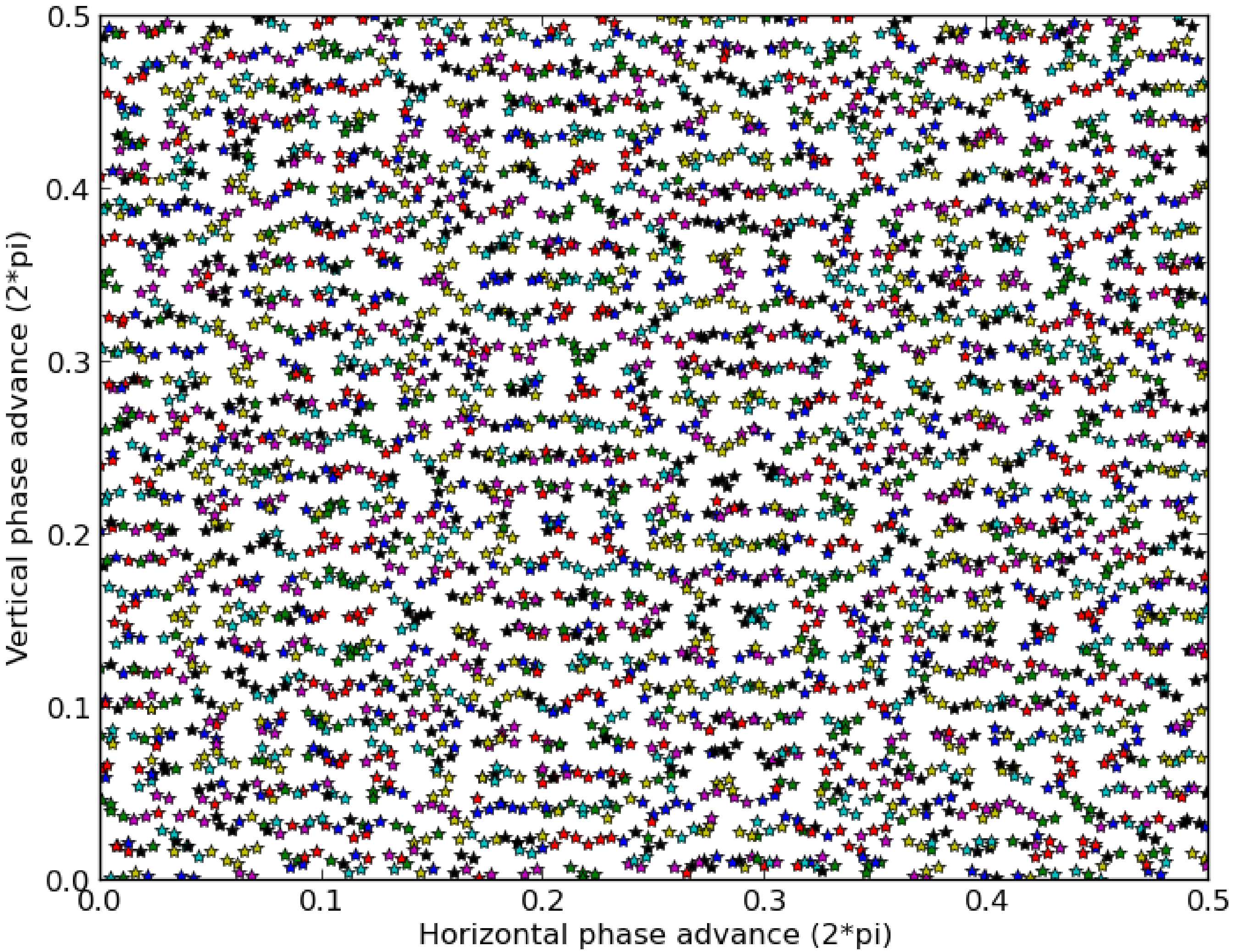
Eigenvalues



Eigenvalues



Phase plot


0.5
0.4
0.3
0.2
0.1
0.0
Vertical phase advance (2*pi)
0.0
0.1
0.2
0.3
0.4
0.5
Horizontal phase advance (2*pi)

Matrix form

For a linac machine with m BPMs and n correctors, the orbit response matrix

$$R = \begin{pmatrix} R_{1,1} & R_{1,2} & R_{1,3} & \cdots & R_{1,n} \\ R_{2,1} & R_{2,2} & R_{2,3} & \cdots & R_{2,n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ R_{m,1} & R_{m,2} & R_{m,3} & \cdots & R_{m,n} \end{pmatrix} \quad (1)$$

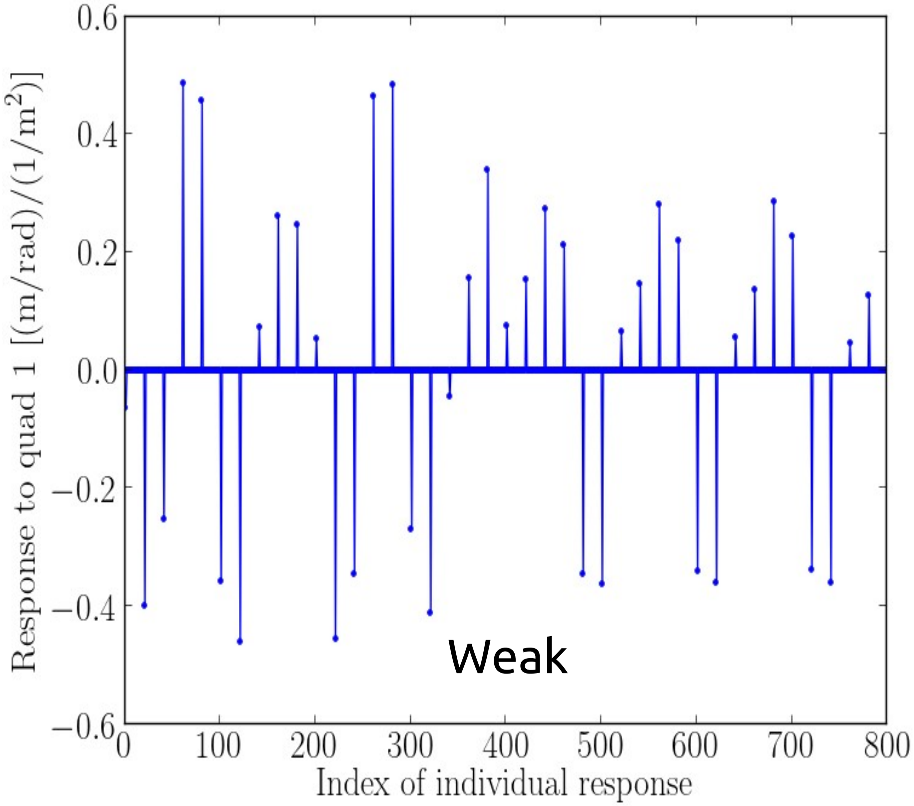
where $R_{i,j} = \begin{cases} \sqrt{\beta_i \beta_j} * \sin(\phi_i - \phi_j) & \text{if } \phi_i > \phi_j \\ 0 & \text{if } \phi_i <= \phi_j \end{cases}$

Vectorize R, the resulted vector depends on gradient error

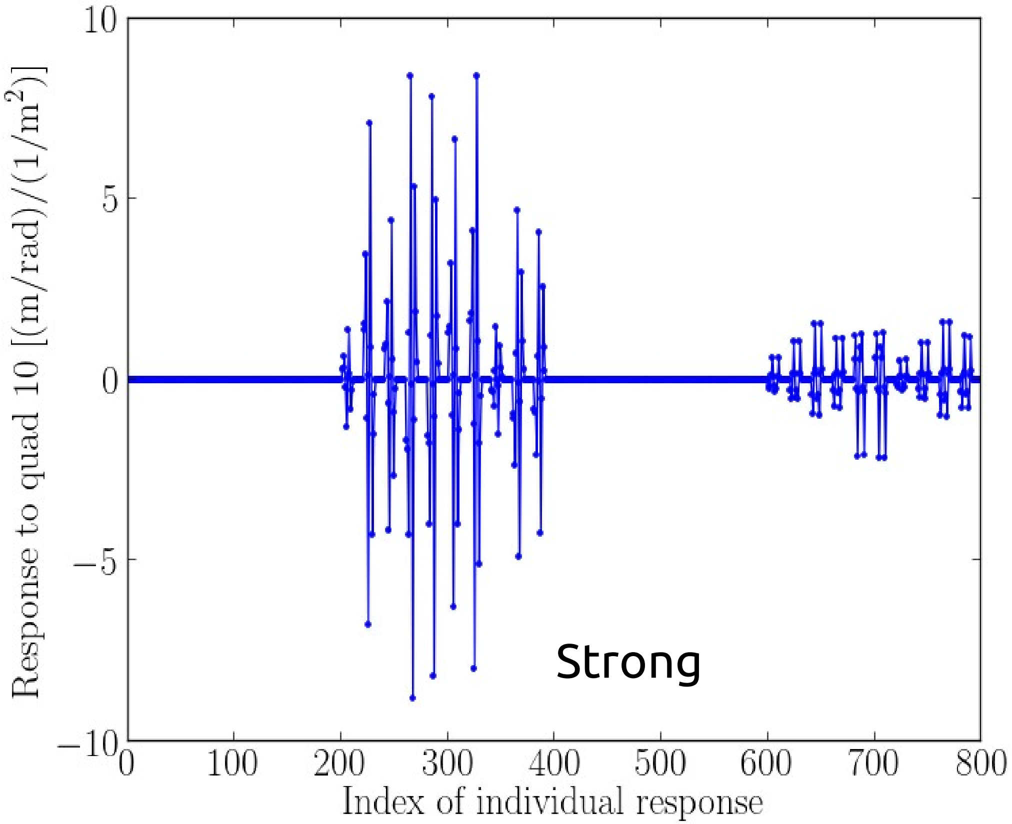
$$\begin{pmatrix} \Delta R_{1,1} \\ \vdots \\ \Delta R_{1,n} \\ \vdots \\ \Delta R_{2,1} \\ \vdots \\ \Delta R_{2,n} \\ \vdots \\ \vdots \\ \Delta R_{m,n} \end{pmatrix} = \begin{pmatrix} M_{1,1} & M_{1,2} & M_{1,3} & \cdots & M_{1,q} \\ M_{2,1} & M_{2,2} & M_{2,3} & \cdots & M_{2,q} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ M_{p,1} & M_{p,2} & M_{p,3} & \cdots & M_{p,q} \end{pmatrix} * \begin{pmatrix} \Delta k_1 \\ \Delta k_2 \\ \vdots \\ \Delta k_q \end{pmatrix} \quad (2)$$

where $p = m * n$, q is number of quadrupole magnets.

Dependence



Response to quad 1 [(m/rad)/(1/m^2)]
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0
100
200
300
400
500
600
700
800
Index of individual response
Weak



Response to quad 10 [(m/rad)/(1/m^2)]
10
5
0
−5
−10
0
100
200
300
400
500
600
700
800
Index of individual response
Strong